Final Report

on

Hazards Monitoring

At NASA Merritt Island Launch Area

VOLUME II

Task B -- Ultrasonic Leak Detectors
for Cryogenics and Gases

Contract No. NAS10-2009

National Aeronautics and Space Administration
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1. INTRODUCTION

This report on Performance and Applicability of Ultrasonic Leak Detectors for Cryogenics and Gases is in response to Task B of Contract NAS10-2009, as amended, between NASA-KSC and Melpar, Inc.

The remaining three tasks under this contract are covered in the following three additional separately bound final reports:

Volume I, Task A -- Sensor Selection and Location for Apollo Fuel Transfer and Tanking System.

Volume III, Task C -- Data Display and Transmission System.

Volume IV, Task D -- Measurements of Incident and Reflected UV and IR Electromagnetic Background at Saturn Complex 37.

2. LABORATORY TEST AND EVALUATION

As required by Task B, section 2 of Exhibit 1 of the contract, laboratory tests were run to determine the relative response of two ultrasonic leak detectors, the Delcon Model 118 and the Techsonics Model 110. Tests have been run to determine the variability of leak noise as a function of leak geometry, pressure, angle from the axis of the leak, and the gas involved.

2.1 Calibration Procedure

In order to measure absolute sensitivity, it was necessary to obtain a calibrated source of sound in the proper frequency range. An inexpensive electrostatic tweeter was found to be capable of producing sufficient energy to be detected at a standard distance by a relatively insensitive B&K Model 4135 standard microphone. The tweeter was connected to a General Radio Model 805C oscillator while it was properly biased for linear operation at a signal level sufficient to exceed the background noise associated with the B&K microphone. Then sensitivity versus frequency measurements were made with the two leak detectors. Figure 1 is a block diagram of the test setups.

During these measurements it was necessary to assume that the tweeter was linear, and, therefore, if the voltage applied to it was attenuated a given number of decibels, the generated sound pressure would be attenuated by the identical number of decibels. Tests at high sound levels (within the usable range of the B&K standard microphone) indicate that this is true. Frequency response and directivity measurements were taken using the subject leak detectors and ac vacuum tube voltmeters as detectors to measure output level. Calibration of the tweeter sound generator was accomplished by

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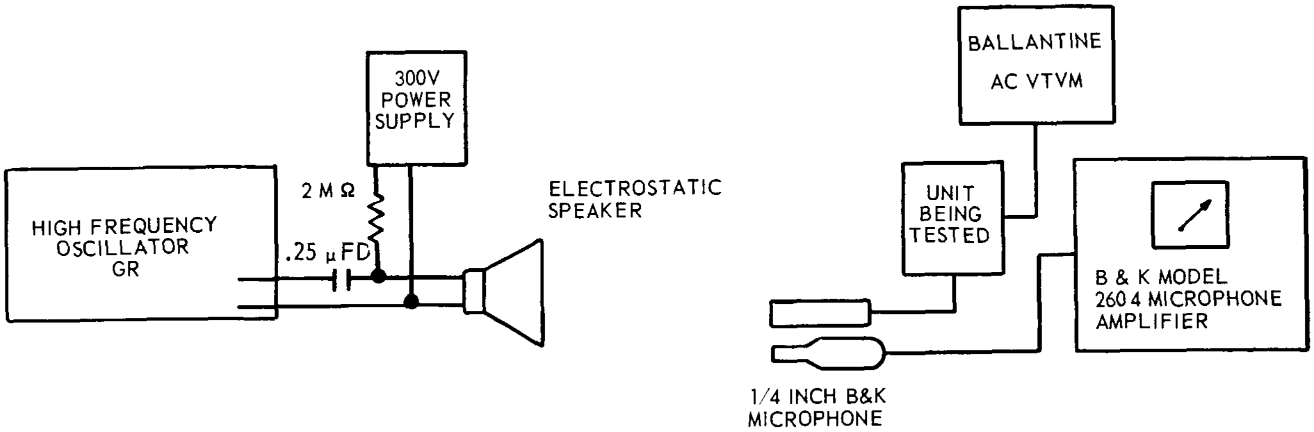


Figure 1. Sensitivity Test Setup and Frequency Response Setup

measuring its output with the standard microphone. The directivity measurements were made at 35 kc by rotating the transducer of the leak detector and noting response at several different angles.

2.2 Test Procedure

Four "standard" leaks were fabricated from 1/8-inch brass pipe plugs as shown in figure 2. These leaks were connected to a pressure regulator and a precision pressure gauge. Tests were run in such a way that maximum isolation of the variables could be obtained. Tests were run with varying gases, hole sizes and pressures. Detection distance was measured and compared point-by-point with the Delcon manufacturer's curve (figure 3), which agreed well with experimental results. However, because detection range is not quantitative, but is a subjective determination, there was some slight deviation between measured results and published data. The setup for these tests is shown in figure 4 and used the B&K microphone, microphone amplifier, and a Spencer-Kennedy variable filter connected so that the meter indicated only energy in the range between 20 to 50 kc.

2.3 Equipment Performance

The results obtained in these tests are shown in table 1 and in figures 5 and 6. It was observed that within their frequency range, both instruments were in the order of 60 db more sensitive than the reference microphone.

Figures 5 and 6 are smoothed normalized plots of the frequency response and directivity of the units tested. It was necessary to exercise care in the measurement procedure to avoid the effects of standing waves. The notch on both curves is due to limitations in the audio response of the two units

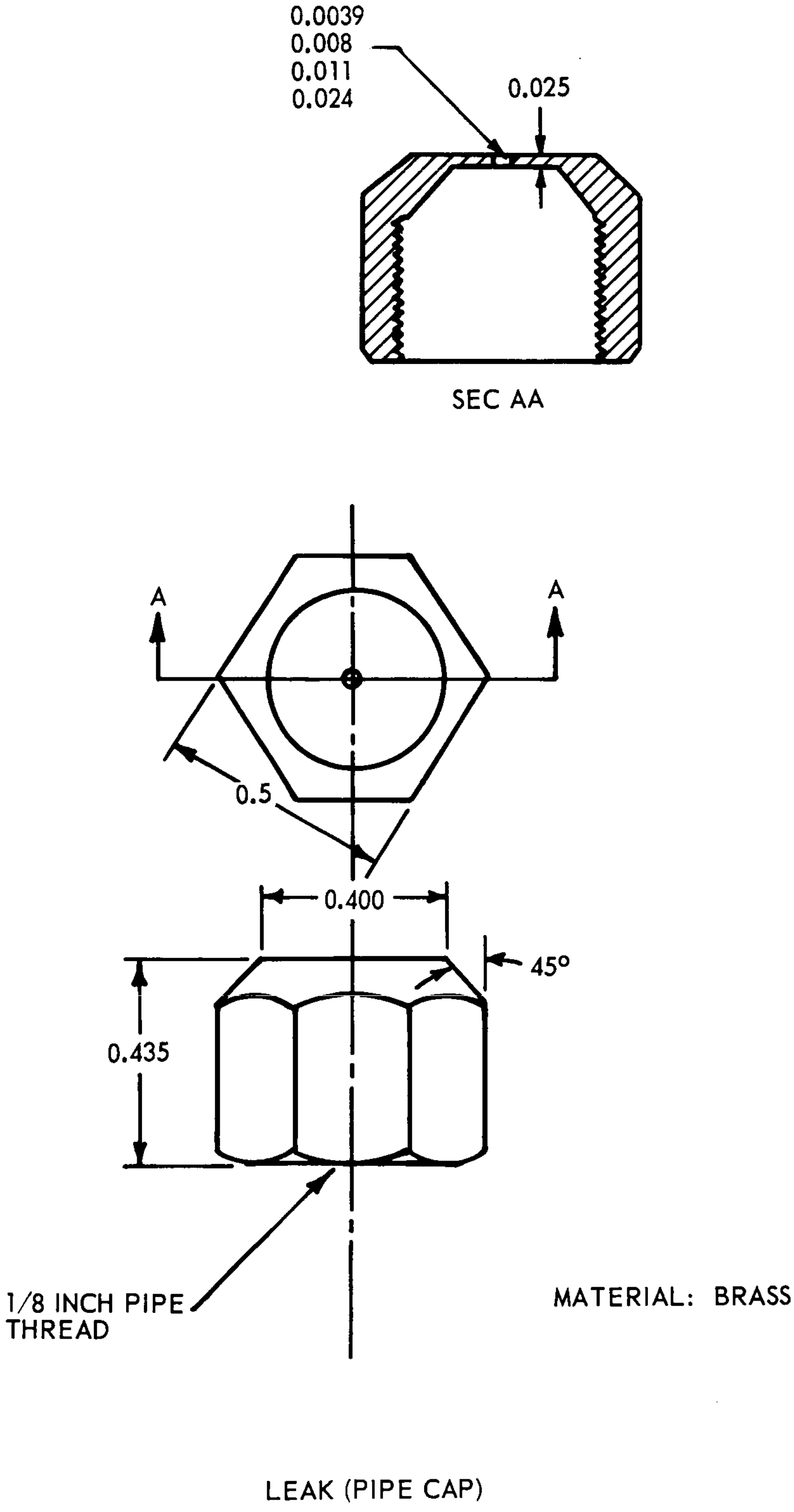


Figure 2. Leak (Pipe Cap)

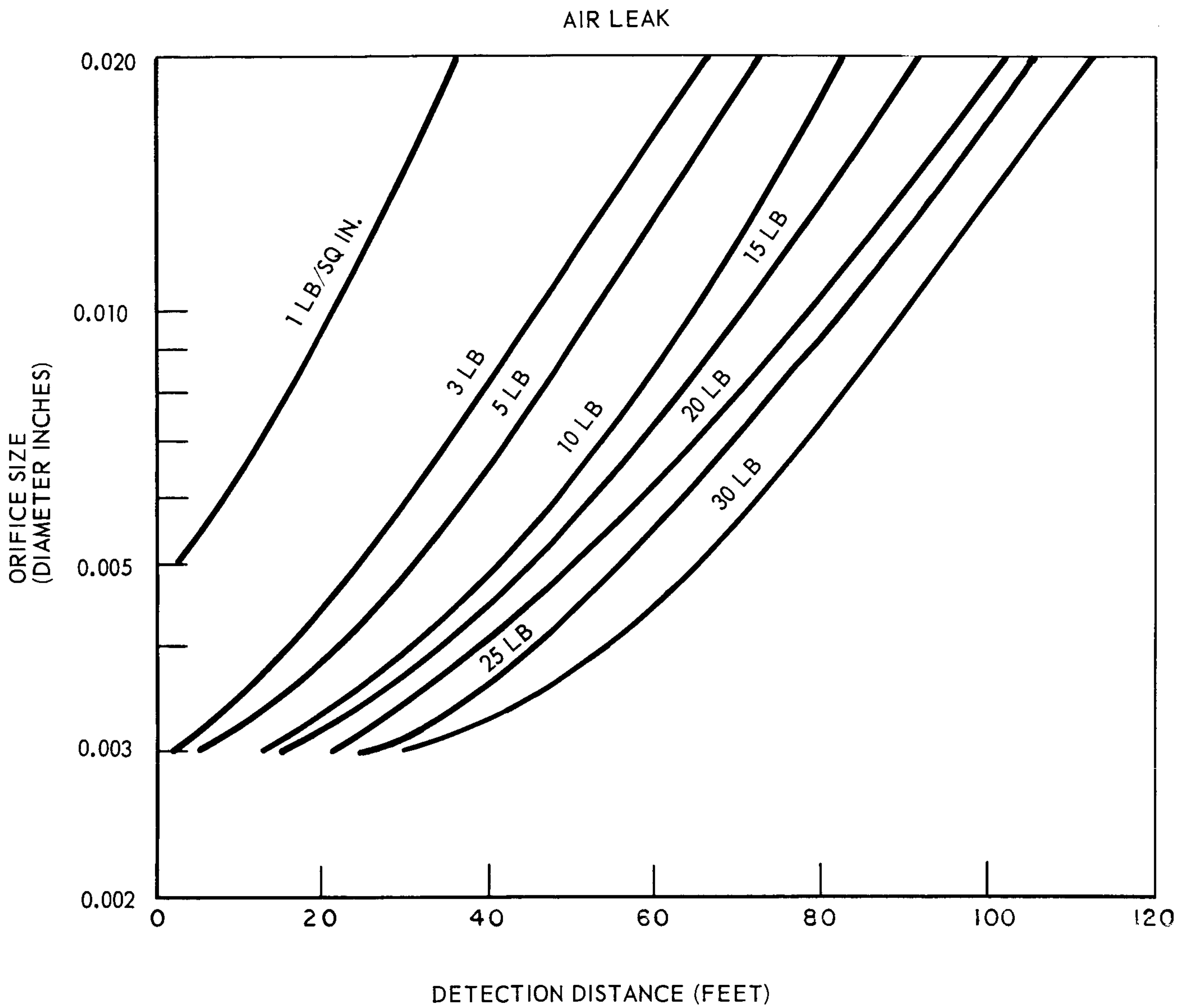


Figure 3. Detection Distance (feet)

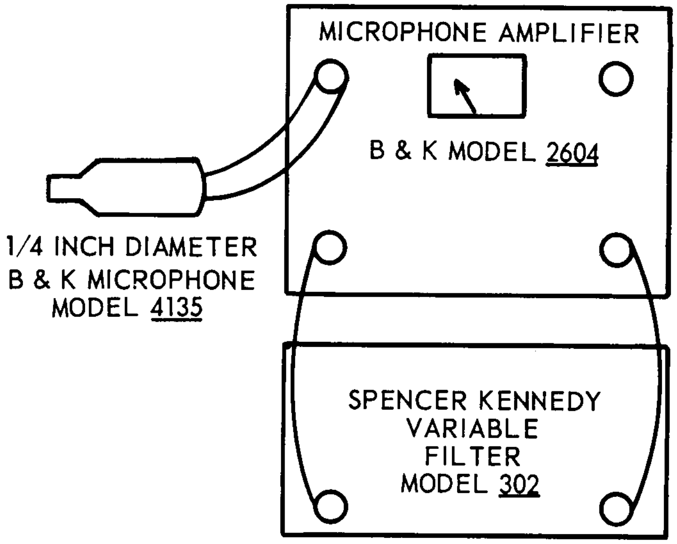


Figure 4. Test Setup for Detection Distance Measurements

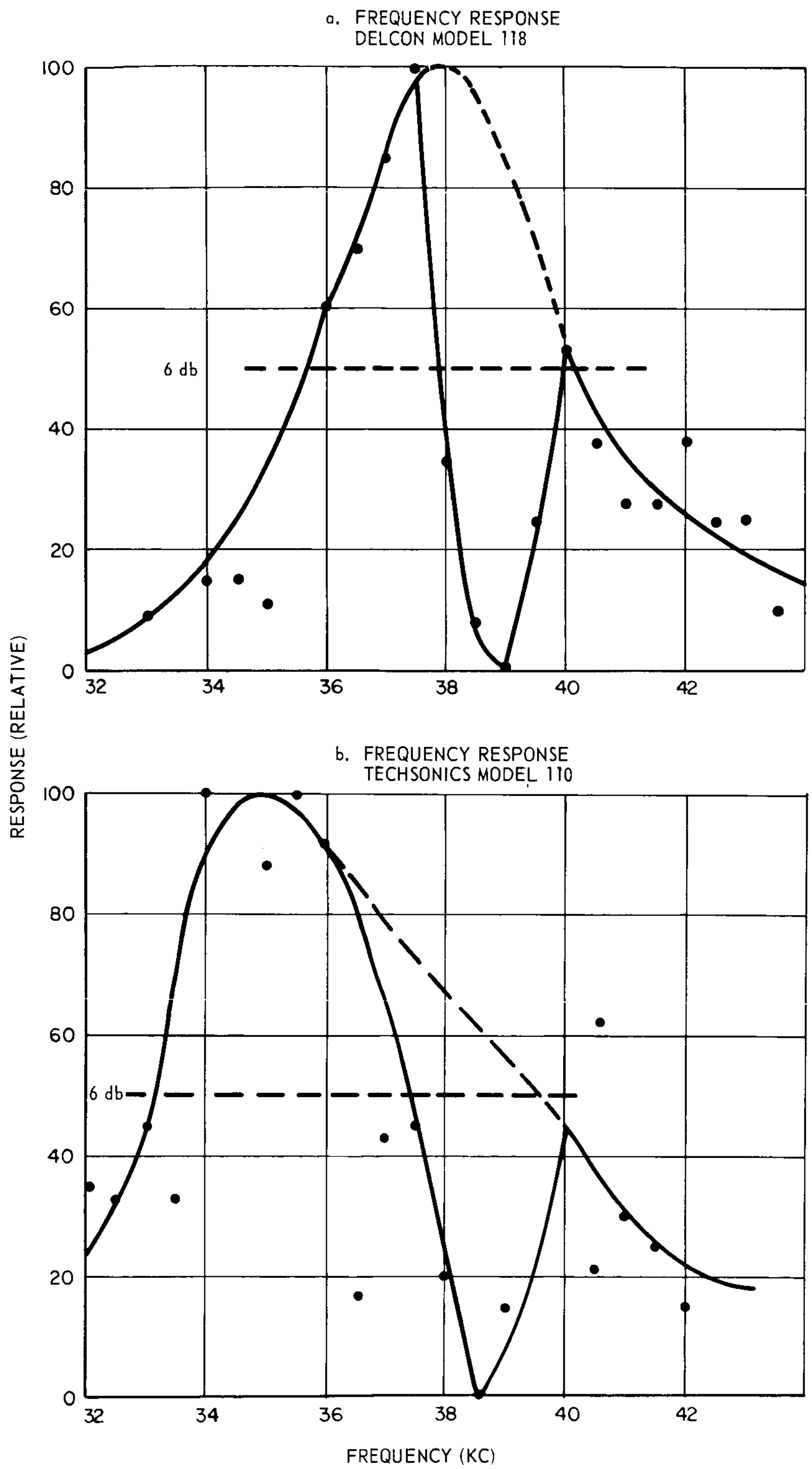
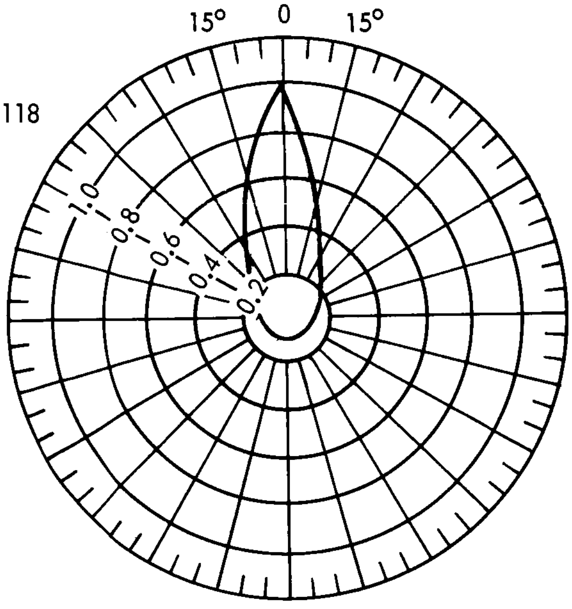


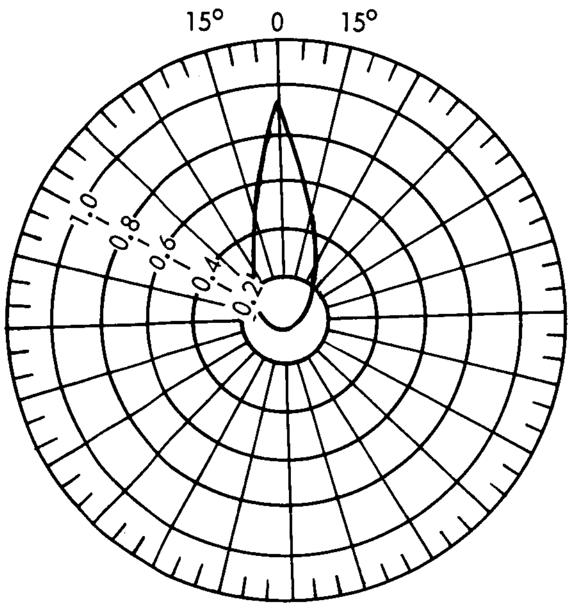
Figure 5. Equipment Frequency Response

a. DELCON MODEL 118



a

b. TECHSONICS MODEL 110



b

Figure 6. Equipment Directivity

as the incident signal frequency approaches zero beat with the internal local oscillator (heterodyning) signal.

TABLE 1

EQUIPMENT PERFORMANCE

	Sensitivity(db)	Frequency Response(kc)	Directivity(deg)
Delcon 118	-8 db at 38 kc	35.5 - 40.2	35
Techsonics 110	+2 db at 37 kc	33.0 - 39.5	27

Notes: Sensitivity referred to 0.0002 microbar.
Frequency is referred to 6 db down points.
Directivity is referred 6 db for down points.

These results indicate that the Delcon unit has a 10-db sensitivity advantage over the Techsonics unit. The Techsonics unit is somewhat more directive, however, which is probably due to its larger transducer. Relative sensitivity is based on the sound level necessary to double the metered output from the unit, where the first meter reading is for noise alone, and the second is for signal plus noise.

The Delcon hand-held transducer proved to be 6 db more sensitive than its corresponding hand unit which has a longer cord. The difference is attributed to capacitive loading by the longer cord.

Figure 3 is a copy of the curve supplied with the Delcon unit that indicates the approximate distance over which an air leak of given orifice and pressure should be detectable.

2.4 Spectrum of a Gas Leak

Spectrum analyses were made to determine the relationship between leak geometry and spectral distribution. All tests run indicate that for a given distance there is no change in spectrum caused by hole size or pressure.

However, due to selectively greater attenuation of high frequencies in air, there would be a measurable change as a result of varying distance. This effect would shift the peak of the spectrum toward the lower end. Figure 7 shows the spectrum of a leak taken at 5-1/2 feet. The energy below 2000 cps is probably all room noise, and was below the threshold of detectability on the scale used above 3000 cps. This spectrum was taken by connecting the output of the 1/4-inch microphone and the B&K model 2604 microphone amplifier to a Hewlett-Packard Model 302A harmonic analyzer with a motorized sweep drive. The detected output was recorded on a Honeywell strip chart recorder from which the data of figure 7 were taken. The energy generated by the leaks appeared to "scintillate" considerably, so that the chart shows a band of intensities for each frequency. The peak-to-peak amplitude of this band is about one-half the absolute value of the average level. The cyclic variation in the spectrum above about 22 kc is attributed to the effects of standing waves.

2.5 Synthesis of Sound Level Equation from Leak Parameters

Figure 8 is the manufacturer-supplied response curve of the B&K microphone. Figures 9 through 11 are plots of sound level versus leak supply pressure, hole diameter, and molecular weight. These indicate that the sound level is a function of the first two parameters and a linear inverse function of the third.

The plot of sound level versus pressure is plotted for three different hole sizes, and it may be observed that the slope is different for each hole size. This effect was taken into account as a modifying factor in equations (1) and (2), even though it is possible that the effect may be due to the

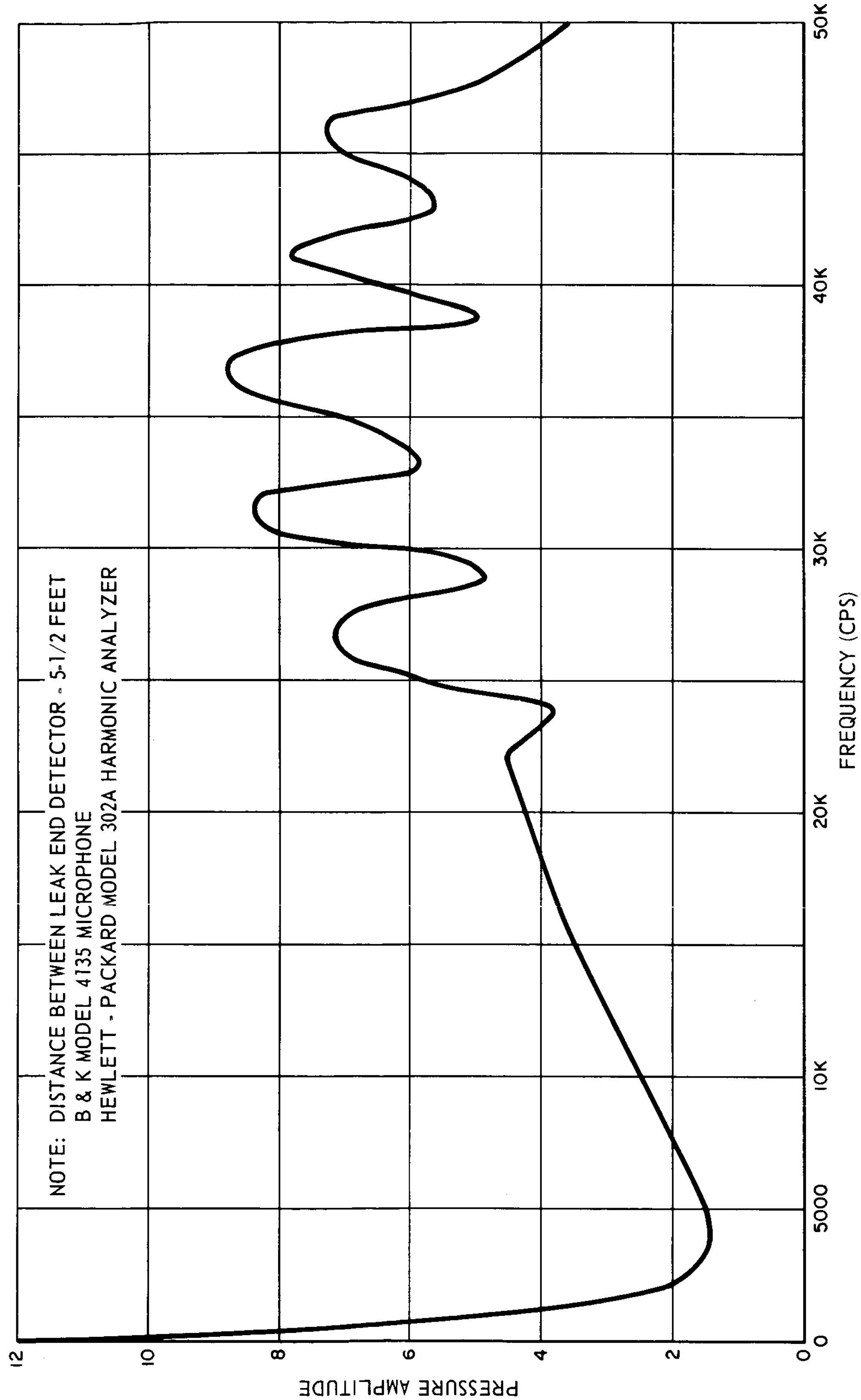


Figure 7. Typical Leak, 40 psi 0.024 in. Leak

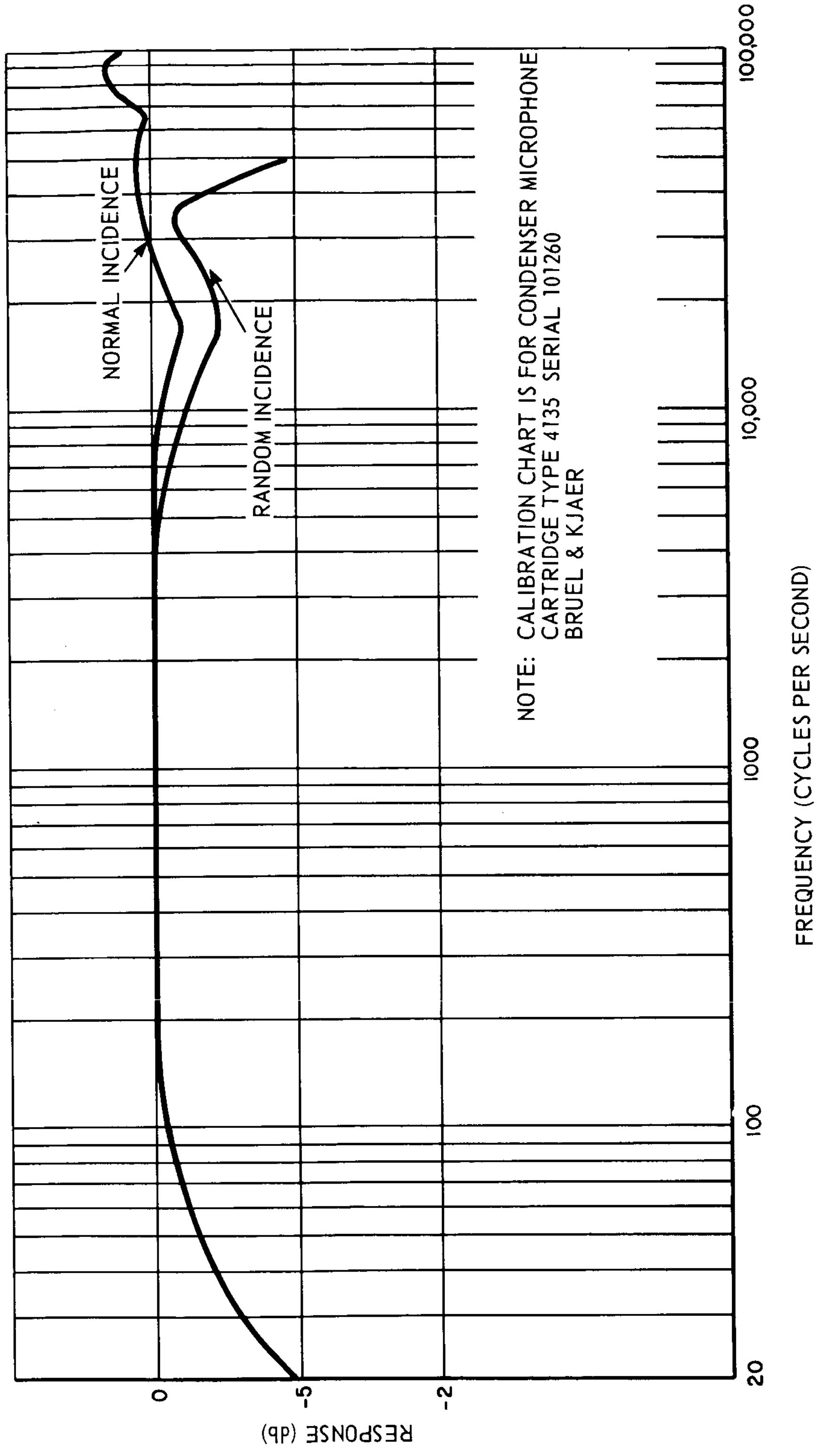


Figure 8. Calibration Chart

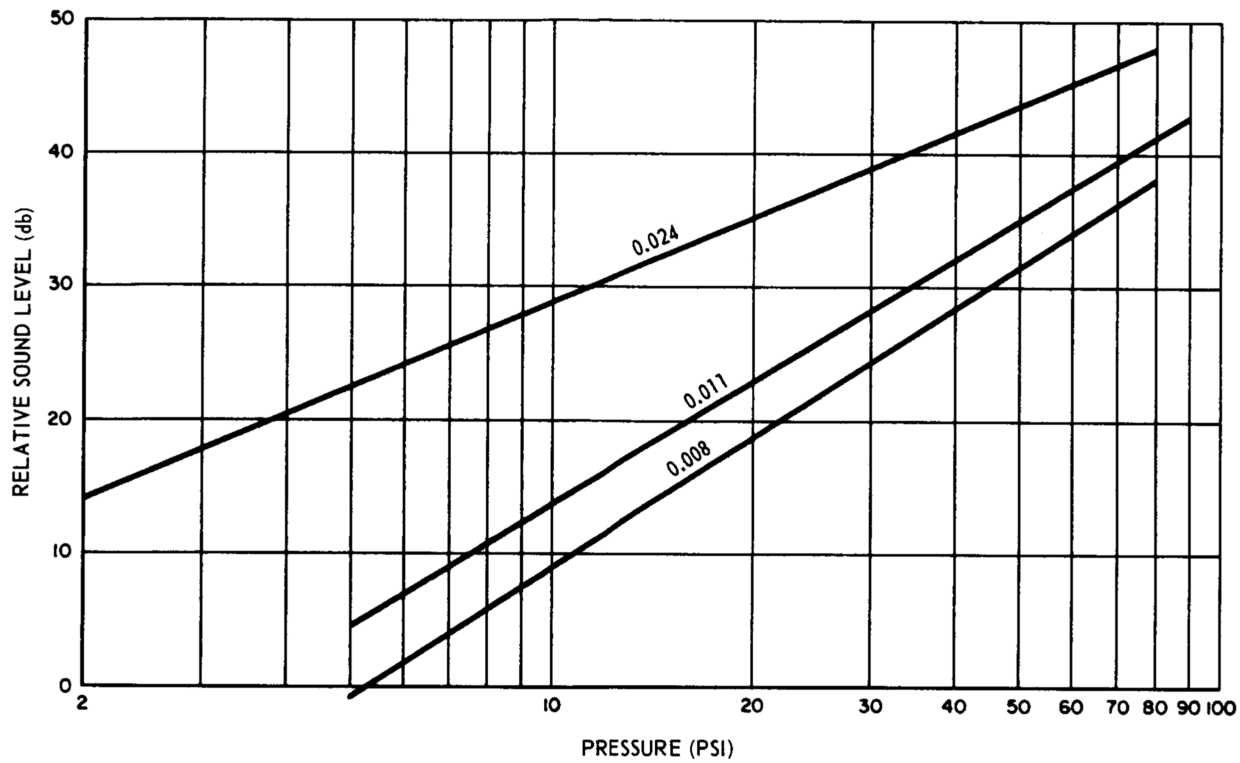


Figure 9. Sound Level vs. Air Pressure

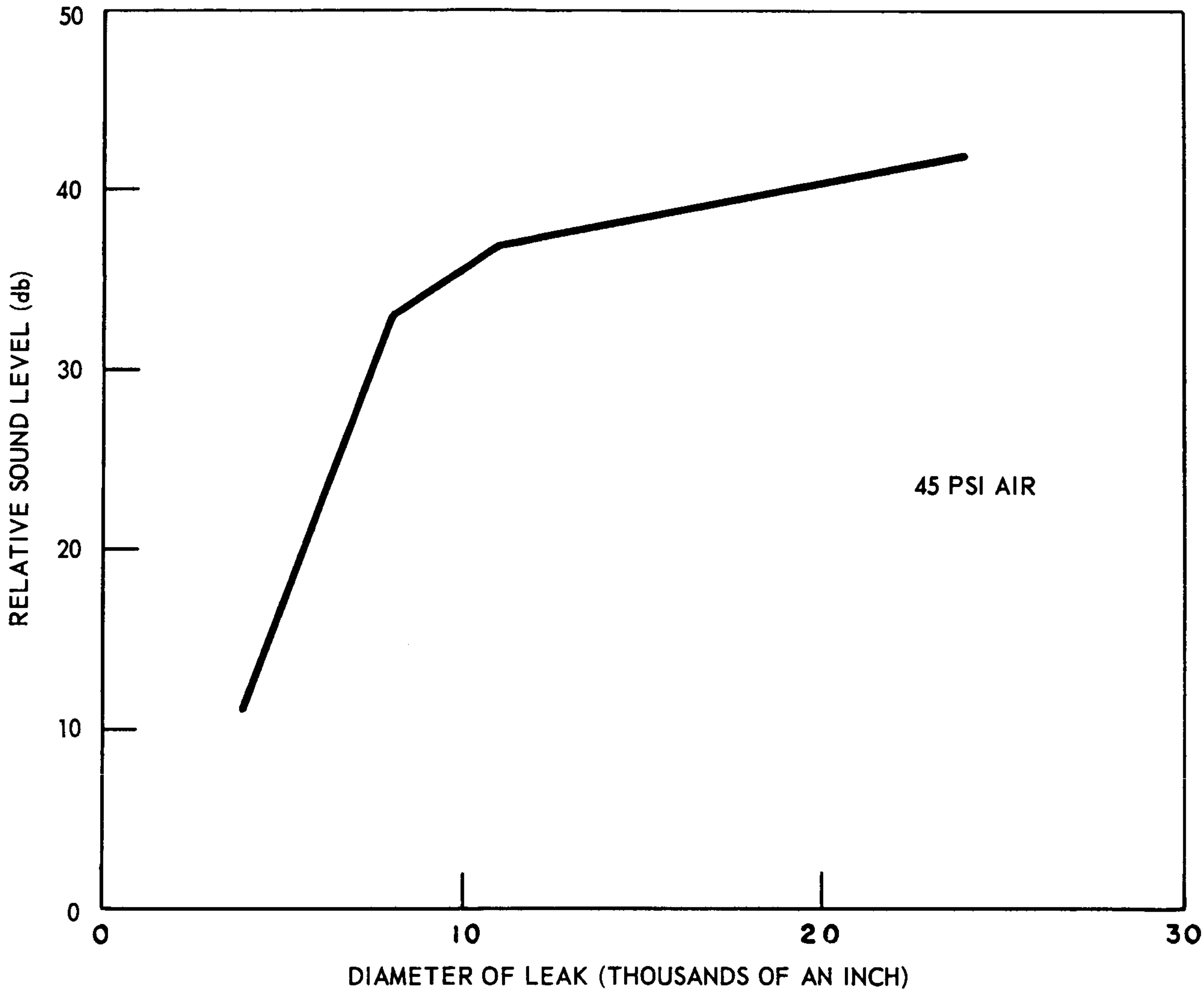


Figure 10. Sound Level vs. Leak Size

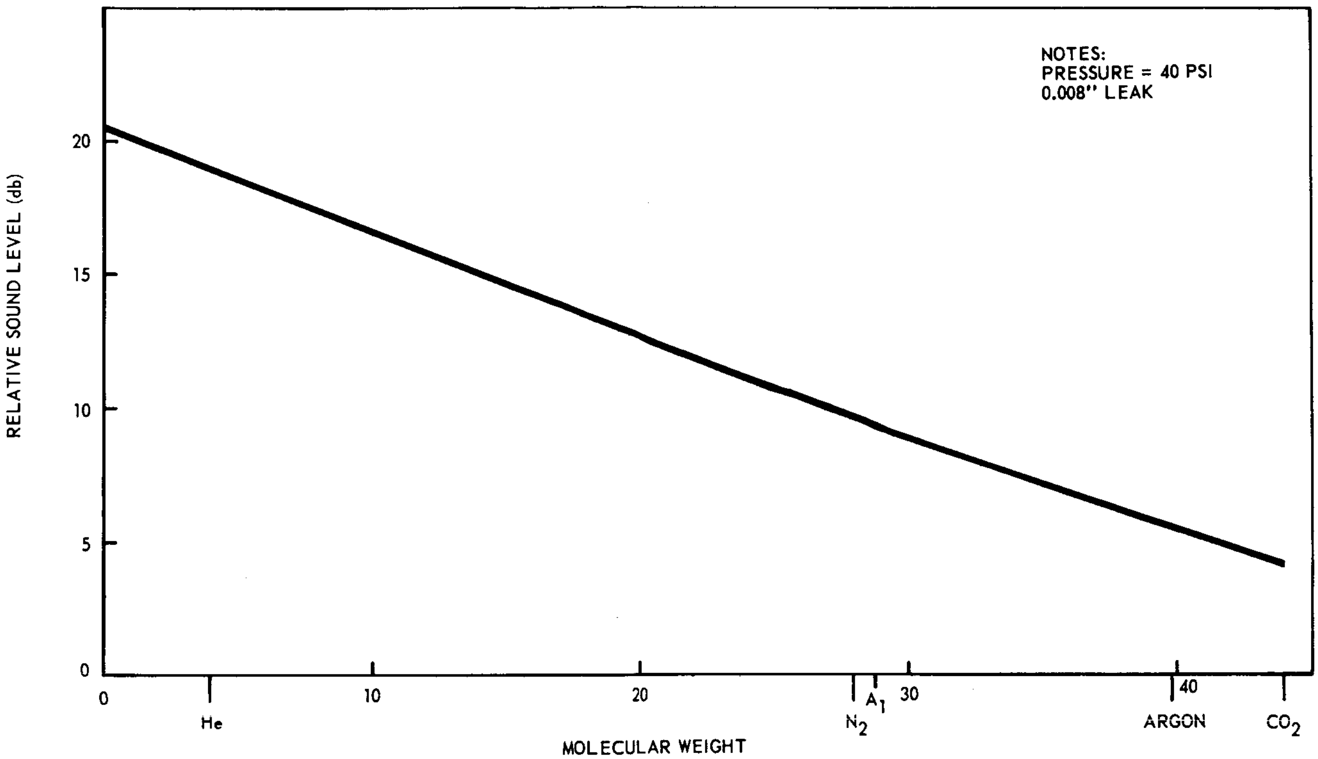


Figure 11. Sound Level vs. Molecular Weight

holes being small in diameter in relation to their length. With these small holes it was not possible to isolate this possibility. From figure 2 it may be seen that for the smallest hole the length is 6 times the diameter. Figure 10 is a plot of measured sound level versus leak size for 45 psi air. This curve did not lend itself to analysis as well as the others. Figure 11 is a plot of sound level versus molecular weight. This appears to be linear on linear paper and is nearly so on semilog paper.

A power-type equation was chosen to try to relate all the studied variables to the sound level. By plotting the variables on semilog paper with the linear axis in decibels (already logarithmic), the slope of the curve is the exponent. The results of the curve fitting are:

$$\text{Sound pressure} = k(P)^{1+0.0055/d}(d)^{1.66}(D)^{-D/20}\ (MW)^{-0.55} \qquad (1)$$

In decibels, this becomes

$$db = K + 20(1+0.0055/d)\log P + 33\log d - D\log D - 11\log MW \qquad (2)$$

where: d = hole diameter in thousands of an inch

P = pressure in pounds per square inch

D = distance to the detector in feet

MW = gas molecular weight (28.8) for air.

K and k are constants where $K = 20 \log k$, and K is equal to 35. This equation assumes that the detector is 20° off the axis of the leak, where sound level is a maximum. Figure 12 shows the sound level as a function of angle off-axis. As may be seen, sound level is considerably affected by angle off-axis, with a 13 db change from on-axis to 20° off-axis.

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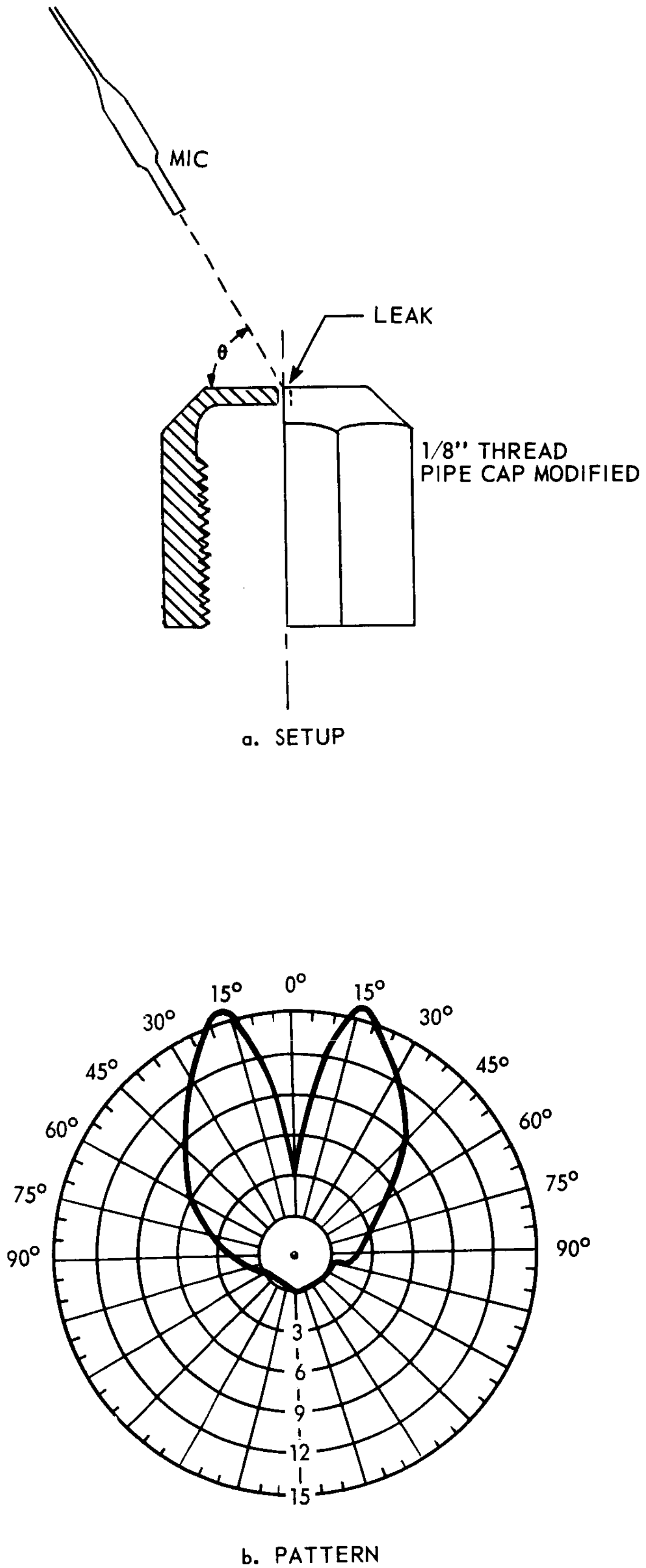

Figure 12. Leak Directivity

3. ACOUSTIC ANALYSIS

In order to evaluate ultrasonic leak detectors for cryogenic systems and to check the applicability of their performance at Kennedy Space Center, tests were conducted in conjunction with Saturn transfer and checkout operations to determine noise and interference background generated by Ground Service Equipment. For this purpose, ultrasonic background intensity levels were measured by microphones placed at the 108-foot oxygen and hydrogen sled level. See figures 13 and 14 of the Launch Umbilical Tower (LUT) at Launch Complex 37, Pad B, during a prelaunch Saturn LOX/LH_2 loading test (test number 6-LLVI-703). More than 1 hour of significant data were recorded on magnetic tape. The ultrasonic spectrum recorded and analyzed was in the range 20 kc to 50 kc. The analyzer filter bandwidth used in data reduction was less than 500 cps at the 3 db point.

3.1 Calibration

No calibration of the B&K microphones was made by Melpar. However, the factory supplied a calibration curve for each unit. The technique used at the factory to calibrate the microphone is known as the electrostatic actuator method, and the response thus derived is for an angle of incidence of 0°. For the microphone used, the output level was 219 microvolts per microbar. Using this constant and the measured gains and losses of the amplifiers and lines, it is possible to determine an absolute value of sound level.

The Delcon unit was not calibrated in the field. It was, however, calibrated in Melpar's laboratory by using the B&K microphone as a standard. Because the Delcon unit contains a front panel potentiometer that controls

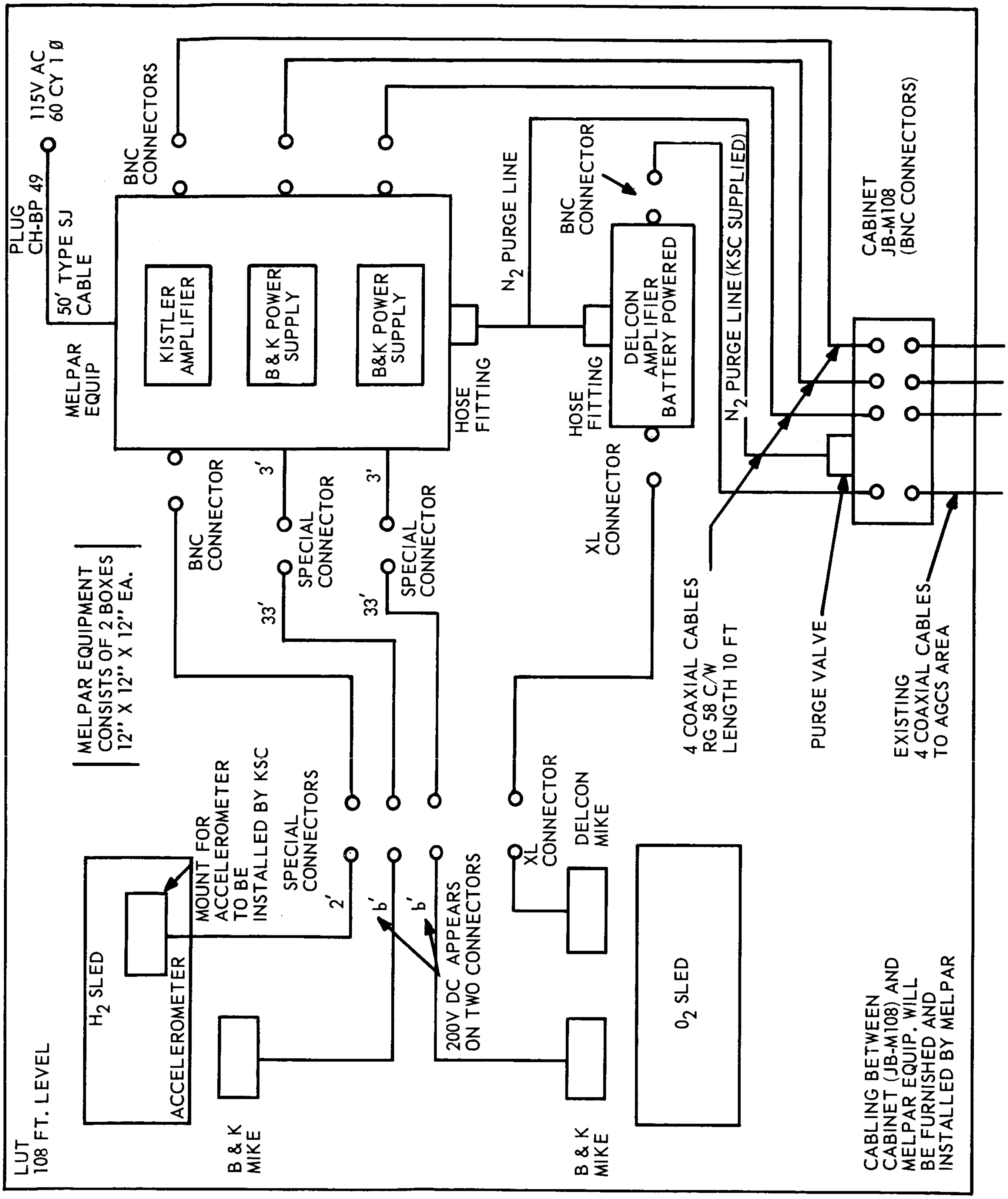

Figure 13. Instrumentation for Sled Area

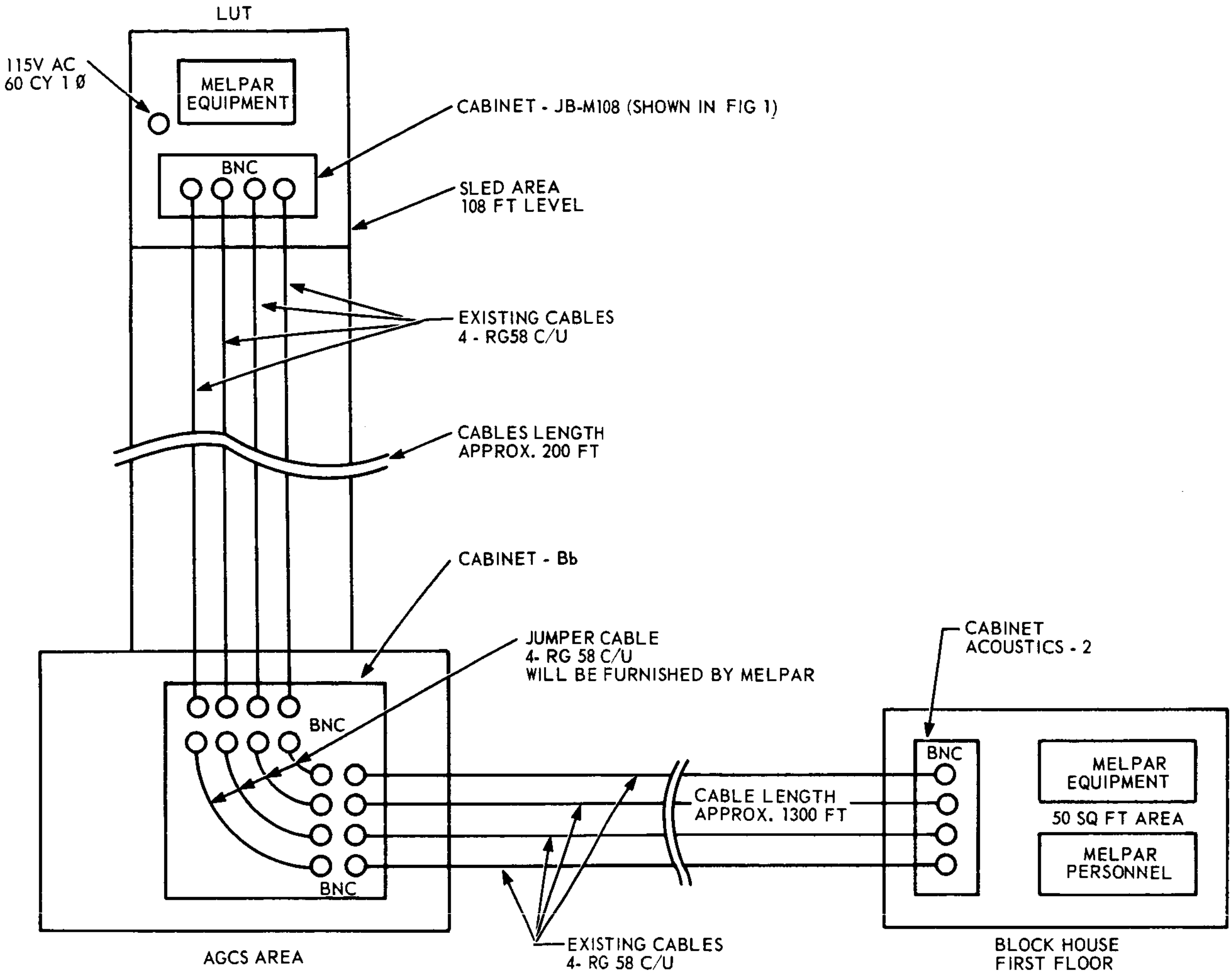

Figure 14. Cabling Requirements for LUT Area

system gain (and output noise), the laboratory sensitivity calibration was made for detectivity of the unit; that is, the acoustic input required to double its output power (signal plus noise). This figure did not change with potentiometer settings. The internal gain of this unit was so great that it could not be used anywhere near its maximum gain setting in the tanking environment.

Two different procedures were available for setting up the Precision Instrument Company tape recorder. One method used laboratory test equipment for inputs, and levels were set at various test points in the circuit. The second method used a PIC plug-in calibrator, which supplied some of the inputs and measured the test point signals with an internal meter. It was found that these two procedures gave similar results, with the exception that one sets the input at 1 volt peak and the output at 1 volt rms, while the other method sets input and output the same. After setup, calibration was performed by injecting a known signal into the recorder and then measuring playback output. This produced a known gain which was combined with all the other gains and losses of the system.

3.2 Data Collection

In collecting leak and vibration data, equipment was arranged in the general configuration of figures 13 and 14. Data from the Delcon Leak Detector transducer, the high-frequency microphones, and voice commentary were recorded on several channels of magnetic tape at KSC and reduced at the Melpar plant. The accelerometer was not used because KSC personnel were unable to attach the Melpar-supplied mounts in time for the test.

The recording site was located on the first floor of the blockhouse behind some audio recording racks in the telemetering room. This site was chosen because it was "out of the way" and yet was adjacent to the terminals of the coaxial cables running to the pad terminal connecting room. In addition, the 28-volt, 2-pps timing signal was available in the vicinity and there was adequate ac power for operating the recording and monitoring equipment. Countdown time was available on the other side of the recording racks, which allowed it to be relayed to Melpar personnel after only a short delay. In general, this location proved to be quite satisfactory.

The tape recorder selected for recording data at KSC was a 7-channel Precision Instrument Company machine, Series PS-200A, operating at a tape speed of 30 inches per second. In order to obtain the required bandwidth of 50 kc, the direct mode of recording was used. The manufacturer's specifications for this instrument at 30 inches per second are response flat to within $\pm$ 3 percent between 50 and 50,000 cps with signal-to-noise ratio of 28 db. These specifications were verified in the laboratory; the frequency response was found to be considerably better than specified, but the signal-to-noise ratio was as quoted. The other specifications, including start and stop time, flutter, and rewind time, were considered noncritical. Cape time signal and voice commentary were recorded on an FM channel that had frequency response from 0 to 5000 cps with a signal-to-noise ratio of 43 db.

The microphones were located in the area of the hydrogen and oxygen sleds on the 108-foot level of the LUT. (See figures 15 and 16.) Of all available locations, this one was expected to produce the most significant data. Only one pickup site could be used because it was not possible to move

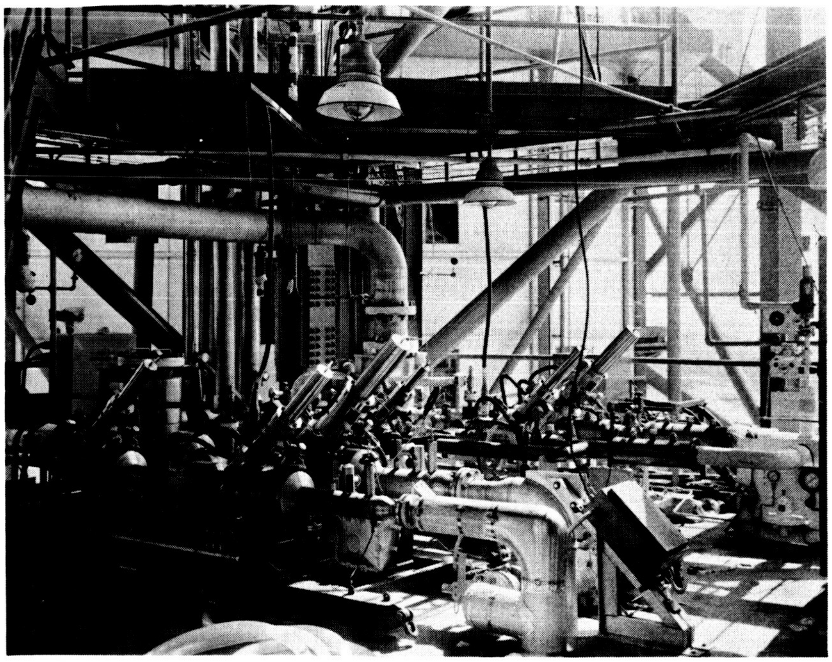

Figure 15. Hydrogen Sled (108-foot Level 7)

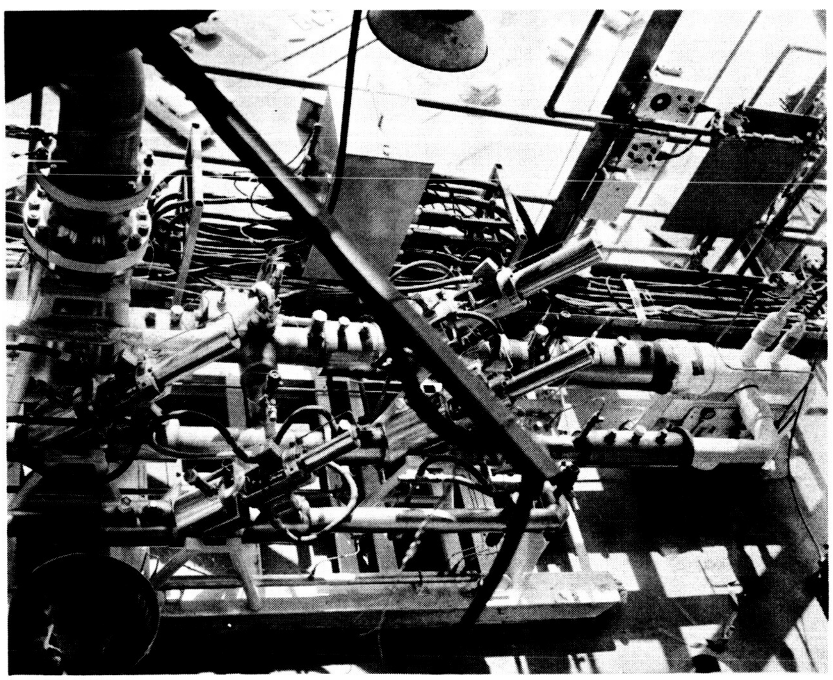

Figure 16. Top View of Hydrogen Sled

the equipment and set up in another location during the tanking test. The sled area on the 108-foot level seemed to have all required facilities: access to coaxial cables running to the blockhouse and 115-volt ac power, as well as proximity to the valve complexes to be monitored. The microphones were placed as nearly as possible directly over the valves on the sled by suspending them from existing beams and braces.

The majority of test data were obtained from the microphone located 6 feet above the oxygen sled and about 12 feet from the hydrogen sled because the microphone suspended 6 feet above the hydrogen sled was apparently shorted by rain from a thunder shower which occurred the evening before the test. The Delcon narrow-band transducer was suspended from a beam about 15 feet from the oxygen sled and 17 feet from the hydrogen sled. This unit was pointed toward the center of the two sleds. The microphones and the Delcon transducer were wired to the electronics package located under a metal platform on the north side of the 108-foot level. The microphone signals were then transmitted over 50-ohm coaxial cable to the blockhouse where there were proper amplifiers and terminations. (See figures 13 and 14.) In the blockhouse, the signals were amplified and recorded on separate channels of the tape recorder. It was planned to record data as follows: Cape time, 28 volts at 2 pps; voice giving countdown time and other commentary; Delcon microphone data; and the output of two Brüel and Kjaer microphones at two gain levels (for better signal-to-noise ratios). However, as stated above, only one microphone functioned properly. System calibration was such that 1 volt of the tape recorder was equal to 122 db sound level at the microphone.

The microphones used in the field tests were Brüel and Kjaer 1/4-inch diameter condenser microphones, Model 4135, fitted with a UA0035 adapter and a Model 2615 cathode follower. The cathode follower was connected through 10 meters of Type AO 0028 cable to a microphone power supply (type 2801), which was located in a nitrogen-purged box. The pertinent microphone specifications were: output 0.2 millivolt per microbar; frequency response, essentially flat from 30 to 100,000 cps; and dynamic range, 64 db to 174 db. The specification for cathode follower 2615 is included in that given above for the 4135 microphone. The microphone power supply, when connected for 50 ohm output impedance, added an 18 db loss to the system. Using this unit also reduced the dynamic range of the system to 154 db by dropping 20 db from the upper end.

The accelerometer system that was procured for use on this task was a Kistler Model 805 quartz accelerometer with a Kistler Model 504 universal dual-gain charge amplifier. The accelerometer has a resonant frequency (mounted) of 60,000 cps. The amplifier was adequate to drive a transmission line from the 108-foot level of the LUT to the blockhouse.

Melpar designed and built four special post-amplifiers to boost the signal from the coaxial lines originating at the sleds on the LUT to a level sufficient to drive the recorder. Amplifier input impedance was 50 ohms, and output level was 1 volt rms into 10,000 ohms, matching the PIC recorder. The 28 db signal-to-noise ratio of the tape recorder suggested that some benefit would be derived from recording several of the inputs on more than one channel, with amplification of about 23 db between channels. The original plan was to use the two-channel technique on the accelerometer and the Delcon unit. Because KSC personnel were unable to attach the accelerometer mounts to the sled, two additional recorder channels became available, and one of these was used for voice commentary, which previously was to be shared with the channel carrying Cape time.

The amplifier used in the B&K circuit directly affects the accuracy of the data included in this report. This amplifier was, therefore, tested in the laboratory and its 45 db gain found to be flat to within about 1 db over the frequency band of interest. In order to eliminate the low frequencies associated with power line crosstalk, a low-frequency rolloff network producing about 40 db attenuation at 120 cps was added to the amplifier. The arrangements for the Delcon channels provided a terminating resistance connected to track one of the recorder and a 23-db amplifier connected to track two of the recorder.

Data and voice were transmitted between the 108-foot level of the LUT and the recording site over existing KSC-supplied coaxial cables. These lines ran from the nitrogen-purged electronics package on the 108-foot level to the pad terminal connecting room at the base of the LUT, where they were patched to other coaxial lines running to a cabinet in the telemetering room on the lower level of the LC-37 blockhouse. The cables were found to have crosstalk and noise ranging between 1 and 15 millivolts. When these lines were connected to grounded equipment that supplied a return path for the outside conductor, the noise level increased considerably. It was found that this situation was normal for coaxial lines at the Cape and that the method universally used to mitigate the effects of noise pickup is to transmit signals at a high level (which accounts for much of the pickup) and to terminate the lines in a transformer, which allows the outer conductor to be floating. A possible solution to the crosstalk problem would have been to amplify heavily at the sending end of the line and have the signal level much higher than the noise. However, the equipment could not be modified in time to accommodate the situation. Fortunately, the crosstalk consisted mostly of low frequency power line interference which was outside the band of interest. On one of the channels there was crosstalk coming from 24 or 48 kc signals carrying timing information code similar to the 2 pps Cape time code format.

A high-level crystal microphone and an adjustable gain amplifier having a maximum of 22 db of gain were used to get the countdown time and other general information onto the tape. It was originally intended to time-share the voice and Cape time onto a single tape channel, so that the amplifier had provision for accomplishing this. When the extra (accelerometer) channels became available, switching of input to the amplifier was not necessary.

Cape time was recorded on the tape by feeding the 28-volt, 2 pps time code information directly into the FM channel of the recorder, with the input attenuator set to avoid overload of the FM record channel. No problems were encountered in this procedure; it was possible later to determine the time of any event by recording the output on a strip chart recorder.

3.3 Data Reduction

The requirement for the analysis of the data was to cover the band from 20,000 to 50,000 cps with a filter bank having no more than 500 cycle bandwidth filters. The first step in signal analysis was to reproduce the original tape on an Ampex Model FR 1200 machine operating at 60 inches per second. In order to fit the 20- to 50-kc data into Melpar's 100-section, 1- to 2-kc filter bank (see figures 17 and 18), the tape speed (and frequency spectrum) was reduced by a factor of 32 by playing the 60 ips tape at 1-7/8 inches per second on a Mincom Model C100 tape machine. This operation shifted the upper and lower frequencies of the desired spectrum to 1560 and 625 cps $(\frac{50,000}{32}$ and $\frac{20,000}{32})$. Because the filter bank operates between 1000 and 2000 cps, a further frequency shift of the playback data was necessary. This shift was accomplished by heterodyning the playback signal in a balanced modulator with a local oscillator frequency of 2625 cps and using the difference frequency. It will be noted that this process inverts the frequencies entering the analyzer. The only effect of this inversion was to make necessary reading of the film from the other edge. The resulting signal was then within the band of 2000 cps to 1065 cps. To prevent undesired frequency sums and differences from also appearing in the output, a high-pass filter having a rolloff of 90 db per octave was used to pass only information above 625 cps. A low-pass filter having a cutoff frequency of 2625 cps and a rolloff of 18 db per octave was also used.

The playback signal next went to a General Electric "Vogad," which is a very fast automatic gain control, and from there to the filter bank, which consists of 100 10-cycle filters. At the output of each of the filters is a detector, with each detector connected to a segment of a mercury jet sampling switch. The mercury jet, which rotates at a speed of 60 rps, samples each of the 100 filter sections during each revolution. If the data were

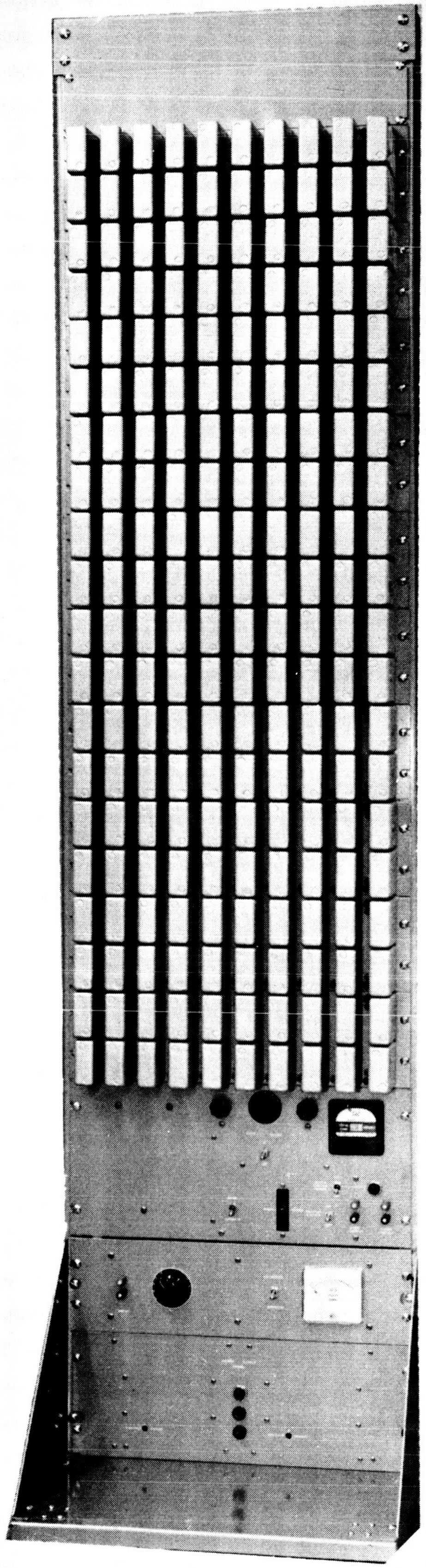

Figure 17. 100 Channel Filter Bank (Front View)

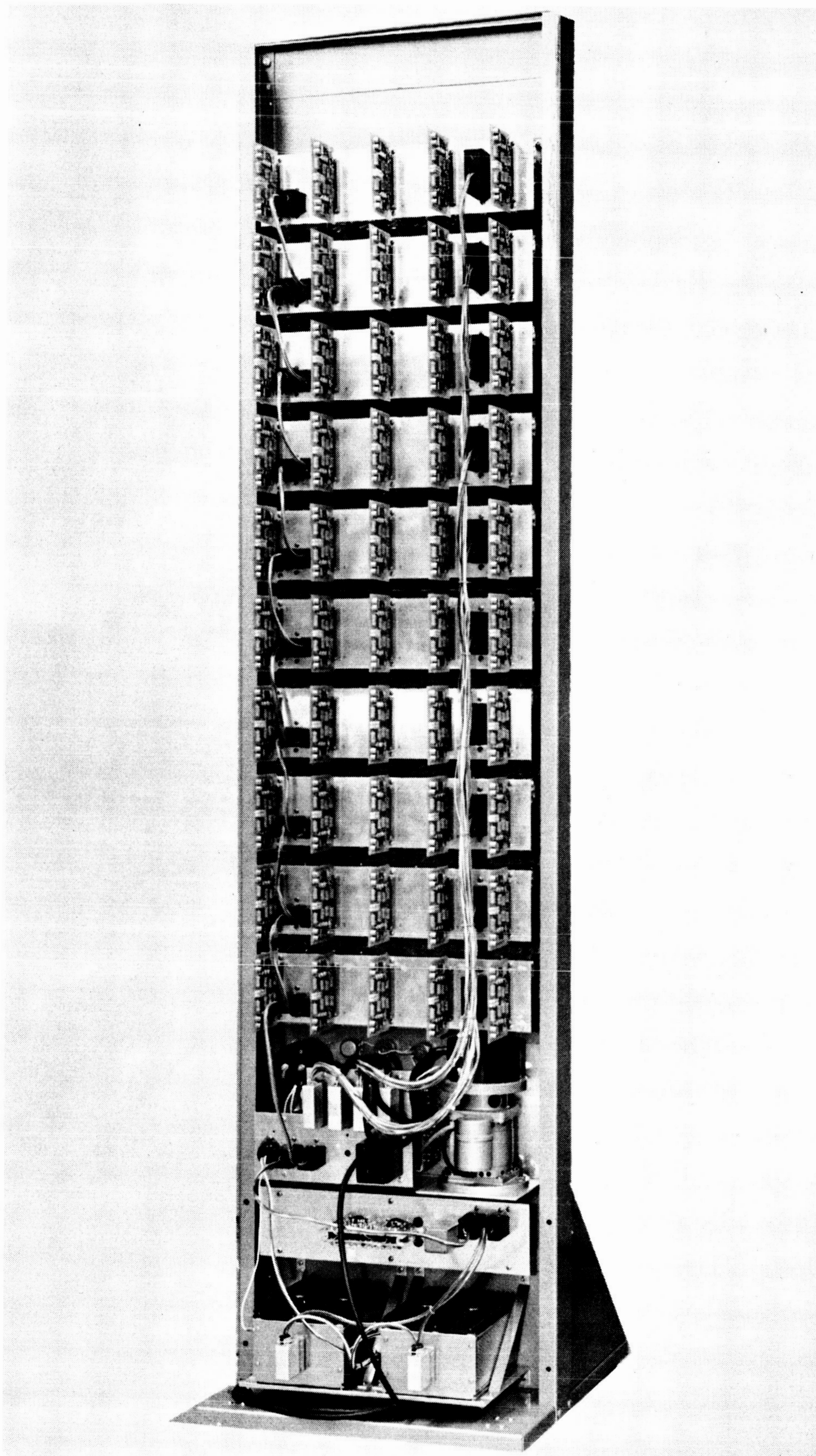

Figure 18. 100 Channel Filter Bank (Rear View)

analyzed at this rate, the effective sampling speed would have been 1920 (60 x 32) samples/second, which would have produced an unwieldy readout. Therefore, a divider circuit was inserted between the sampling switch sync pulse and the readout trigger input. Using this divider, it was possible to classify only one out of each 64, 32, or 16 scans. The output of the sampling switch was connected to both the horizontal and intensity inputs of an oscilloscope. The oscilloscope sawtooth sweep was connected to the vertical deflection plates and produced a display that appeared to be rotated 90° from normal. This was done to accommodate the particular 35 mm continuous motion camera that was used to provide a visual record of the data. The camera had no shutter, and, therefore, each sweep of the oscilloscope was recorded next to the preceding sweep. This sweep system, with Z-axis intensification, produced a very clear recording of the signal frequency, time, and intensity. The rate of film travel is adjustable over very wide ranges in this camera, and for this application it was set for about 60 traces per inch of film. Table 2 lists scanning rate and film speed for the sound spectrograms shown in figures 19 through 24.

TABLE 2

DATA INTERPRETATION

Sound Spectrogram (figure)	Scans per second (real time)	Film Speed, Inches per Minute (actual)
19	60	0.8
20	60	0.8
21	240	2.5
22	60	0.8
23	60	0.8
24	240	2.5

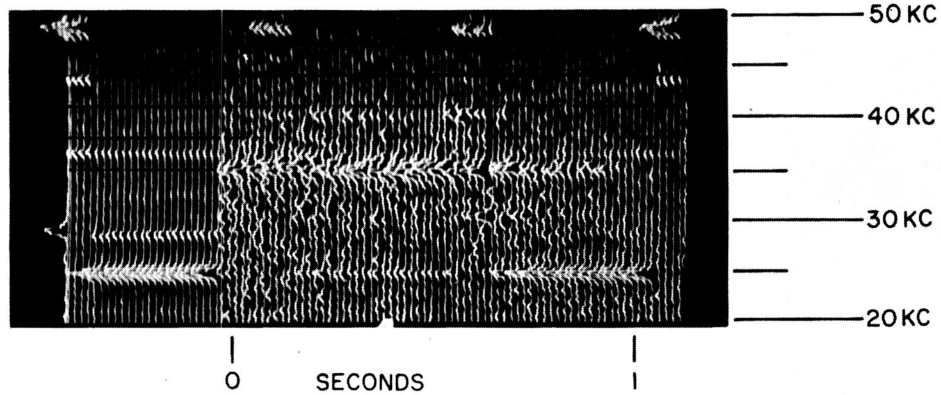

Figure 19. H_2 Valve Operation

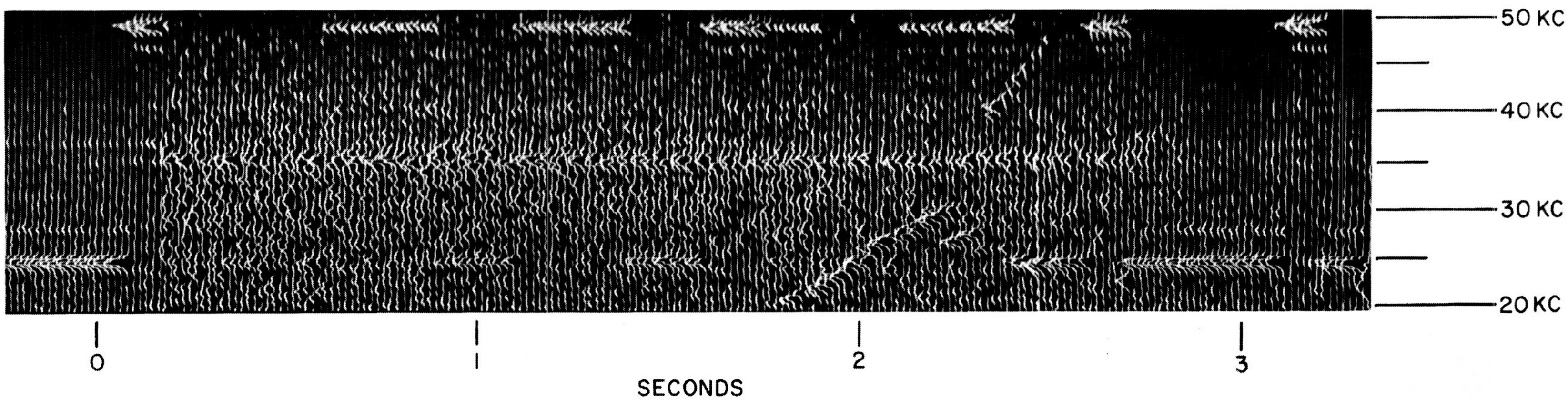

Figure 20. O_2 Valve Operation, 60 Samples/sec

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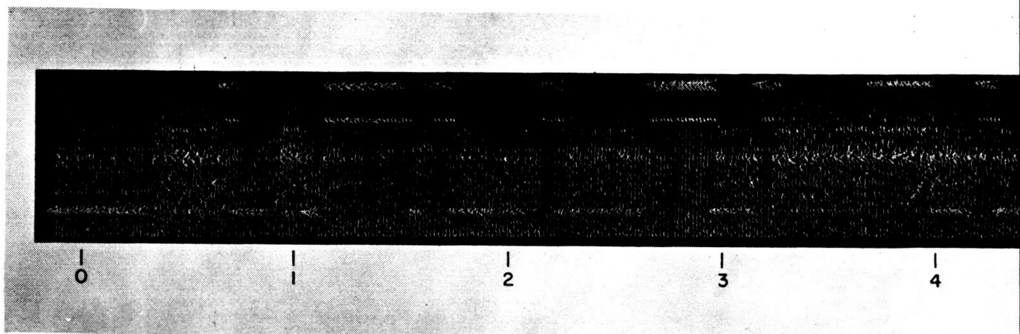

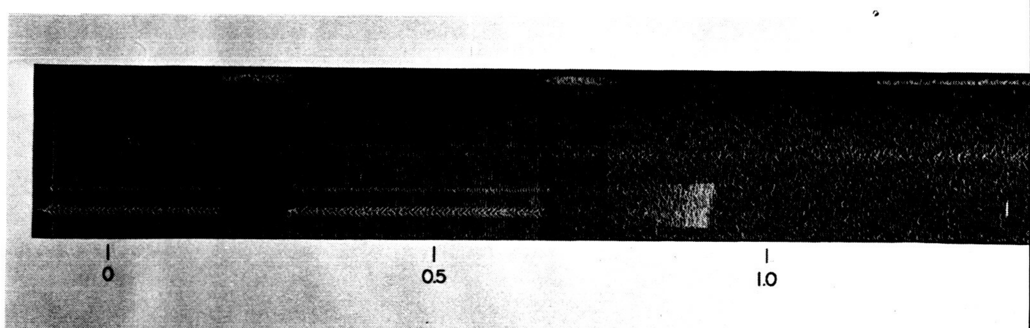

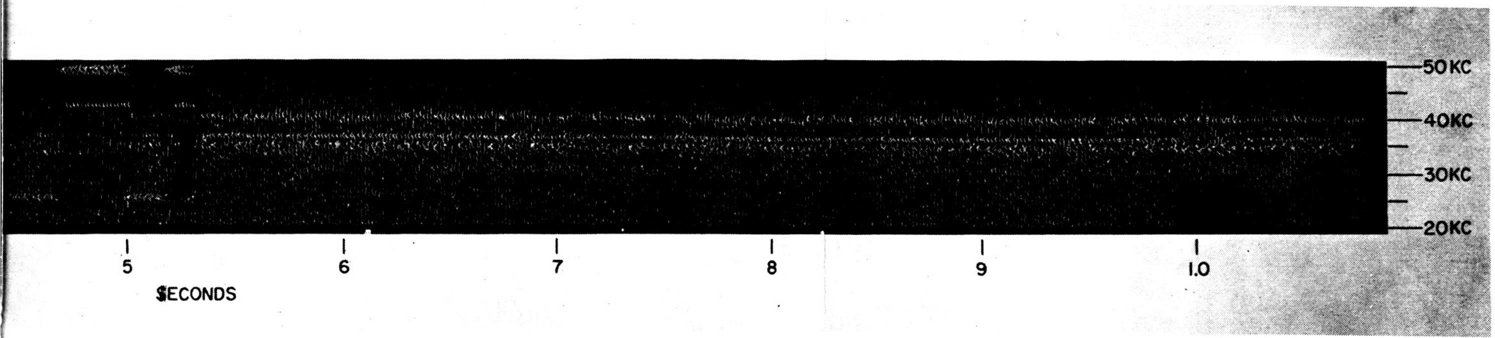

Figure 21. O_2 **Valve Operation, 240 Samples/sec**

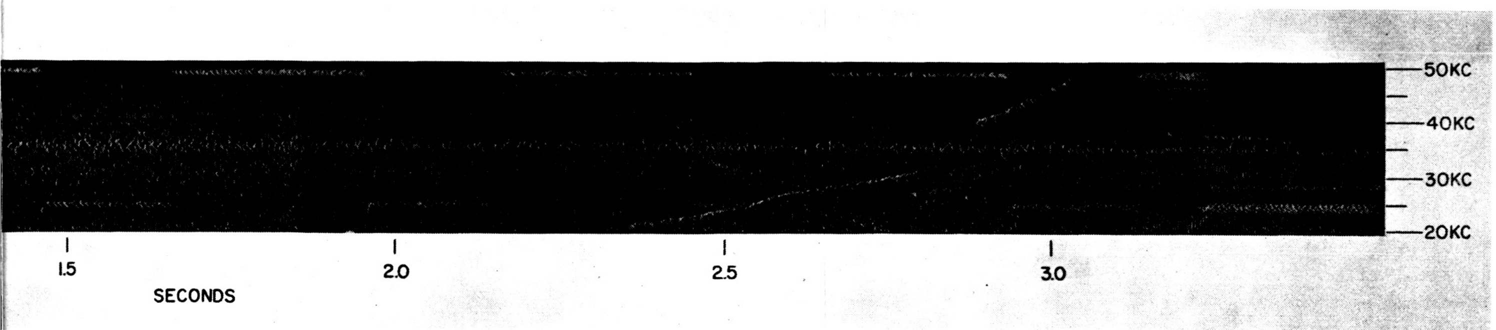

Figure 22. He Valve Operation

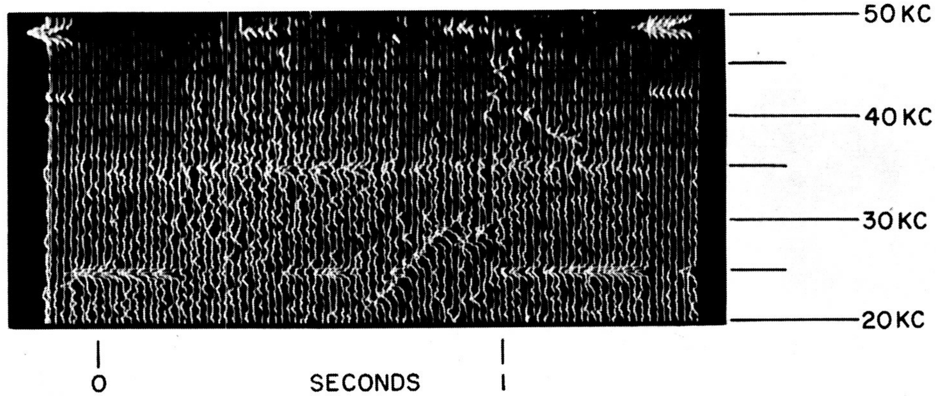

Figure 23. O_2 Replenish Valve Operation, 60 Samples/sec

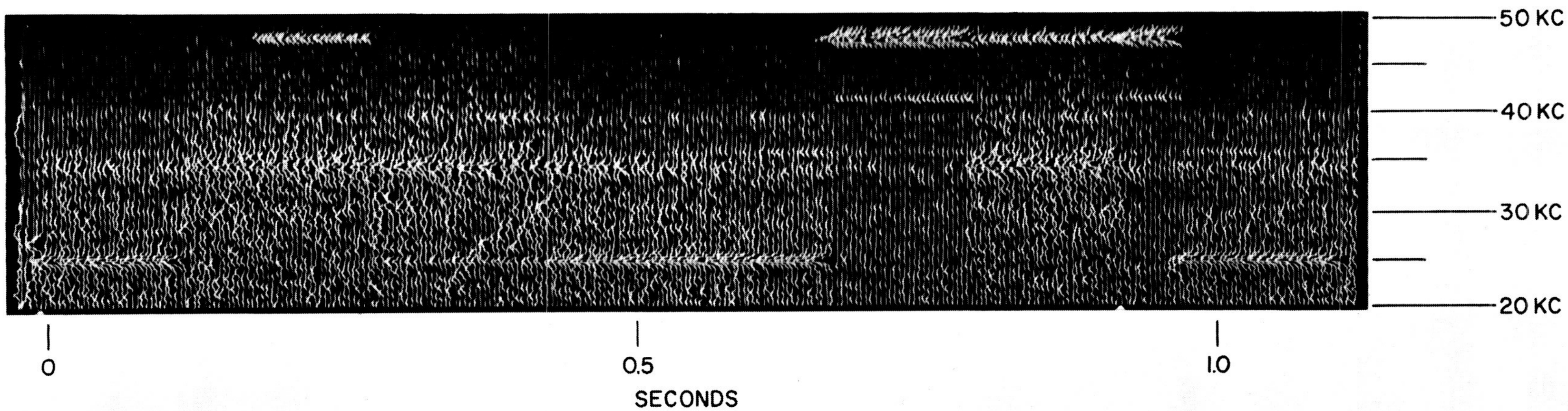

Figure 24. O_2 Replenish Valve Operation, 240 Samples/sec

The spectra of typical noisy events recorded during the tanking test are shown in figures 19 through 24. These events were found on the hour-long tape by inspecting the entire tape for recording level and nonbackground-type spectra. This was done with a low resolution spectrum analyzer and by listening. As a result of this analysis, the 1 hour and 4 minutes of recorded data were reduced to 16 minutes of interesting data for further analysis. The events were then marked on the tape so that they could be found easily later. The operation which caused a spectrally significant event was found by monitoring the voice channel for countdown time and then referring to the test schedule.[1] Range time, although available on the tape, was not used because it did not account for "holds" in the tanking procedure. By this technique it was determined that figure 19, which occurred at T-116 minutes was associated with the hydrogen loading. Figures 20 and 21 were events occurring at T-236 minutes, during the oxygen loading. Figure 22 occurred at T-59 minutes, which corresponds to a helium purge valve operation. Figure 23 was at T-2 minutes and 30 seconds, which corresponds to a LOX replenish phase. Figure 24, at T-1 minute and 20 seconds, most likely shows the signature of a LOX valve operation.

Figure 19 is of a hydrogen valve operation starting from a relatively quiet background. Increasing the relative intensity of the sound is shown as a simultaneous brightening of the trace and a displacement to the left of the flat portion of each individual line. The energy at 20,000 cps is at the bottom of the photograph and 50,000 cps at the top, with a linear distribution of intermediate frequencies between these limits. The black obscuring lines in the upper portion of the photo (figure 19) are caused by the reticule used on the oscilloscope. In the first quarter of the photo the background was low, the Vogad (voice-operated gain control) gain was high, and the crosstalk noise spectra at 24 and 28 kc were very high. With the start of the event these lines are lost as the Vogad reduces the gain many db. It is now seen that there are no very intense lines, but only a general scattering of peaks. In the center of the photo (about 35 kc), there is a peaking of these lines. This tends to support laboratory leak spectrum data. However, it is not known whether this resulting valve operation was produced by an external leak. In the last quarter of the photo the crosstalk is returning almost to its original level. The event is considered over in the last 1/16 of the photo.

The amplitude of the noise distributed over this band was determined by a separate test, which consisted of connecting the output of the PIC recorder through a bandpass filter to a Ballantine ac voltmeter. The signal appearing at the meter movement of the voltmeter is connected to a Sargent Model MR paper chart recorder. This system presumably indicates, with respect to time, the rms energy in the 20- to 50-kc band. For this run it was found to be a peak of 99 db at the microphone.

Figures 20 and 21 are spectrograms of the opening of an oxygen valve taken with two different sampling speeds. The former analysis was done at an equivalent real-time scanning speed of 60 scans per second, and the latter at 240 scans per second. The interesting feature of these recordings are the frequency sweeps, which are apparently characteristic of certain valves. The fact that sweeps were not observed on the hydrogen valve operations is probably due to their being at a higher frequency, which is outside the range of the recorded spectrum. It is judged that the sweeps are produced by the changing dimensions of resonant chambers formed by the plug of the valve and either end. An increasing and decreasing chamber must exist since there are opposing sweeps occurring concurrently. A maximum intensity of 113 db at the microphone occurred during this 2-second event.

The first 1/8 of figure 20 shows background before the oxygen valve opening; it is considerably noisier than the background before figure 19. One possible explanation is to assume that material is flowing during figures 20 and 21 and not during figure 19. As the event of figure 20 starts, the sound level jumps from 100 db to 113 db, and is evenly distributed over the band from 25 to 40 kc. After about 3.5 seconds, a pair of counter-sweeps are seen, lasting about 1 second. Other than the rather intense band at 35 kc, there is no one particular frequency that might interfere with leak detection, since the entire distribution resembles that of a leak.

Figure 22 shows the spectrum of a helum purge valve. About half-way through this analysis, the analyzer was switched from the B&K microphone channel to the Delcon microphone channel so that a comparison could be made of the signals taken from the two devices. The Delcon microphone is a high-output, narrow-band device and responds well only to inputs between 30 and 40 kc. (See figure 5.) When this is considered, the similarity between the first and second halves of figure 22 become more apparent. The sharp line at 36 kc is caused by the leakage of the Delcon local oscillator into its output signal. Both transducers reveal a peaking of energy at about 35 kc. Because of its higher output, the Delcon transducer and line did not have the crosstalk problem that the B&K had, but because it was not readily possible to calibrate this device, no other attempts were made to use it as an analytical tool. The peak amplitude achieved during this photo was 104 db.

Figure 23 is the acoustic spectrum of an oxygen replenish cycle taken at T-2 minutes and 30 seconds. This figure is significant because it shows that there is very little difference in the spectrum generated by different valves. This may be verified by observing that figure 23 is almost identical to figure 20, which is the spectrum of the opening of a similar oxygen valve. The maximum sound level recorded during these operations was 112 db.

Figure 24 shows the spectrum of an oxygen valve closure occurring at T-1 minute and 20 seconds. The real-time analysis speed was 240 scans per second. The maximum sound level associated with this function was 110 db; this level appeared as two peaks of about the same amplitude. By using the crosstalk as a reference, it may be seen that the first peak occurs at the beginning of the photo and the second at about 3/4 of the way down the photo. All the intensities quoted are at the microphone, and some of the variations are due to the varying distances to the valves from the microphone.

3.4 Conclusions

Table 3 indicates that in order to avoid generating false alarm signals from normal valving, the ultrasonic leak detectors would have to be set so that they would be insensitive to a leak at 20 psi* of 0.160-inch diameter. If time-delay before alarm system were incorporated, considerably more sensitivity could be attained. The steady-state noise level either before or after a valve operation seems to run about 101 db at the microphone. This is equivalent to the case of an oxygen leak of 20 psi and 0.071-inch diameter. For nitrogen, this is equivalent to a 0.112-inch diameter leak at 5 psi.

TABLE 3

LEAK EQUIVALENTS OF VALVE OPERATION

Figure No.	Valve	Sound Level (db)	Distance to Microphone (ft)	Equivalent Leak
19	H_2	99	12	5 psi 0.100 in.
20	O_2	113	6	20 psi 0.160 in.
21	O_2	113	6	20 psi 0.160 in.
22	He	104	12	10 psi 0.126 in.
23	O_2	112	6	20 psi 0.152 in.
24	O_2	110	6	20 psi 0.142 in.

It appears from the spectrograms that no high-amplitude disturbance lasts more than 2 seconds, and that, if about 5 seconds of delay were incorporated into the alarm actuator, the detection sensitivity could be fairly high. The generation of an electrical signal to disable the alarm signal during valve operation could be used, but is more complex than the use of a simple time relay or signal integration.

* The pressure used in the equivalent leak column is assumed to be a probable pressure for the material at the 108-foot level at Pad 37. These "equivalent" leaks are assumed to be generated by gas escaping at room temperature rather than at very low temperature.

Examination of these typical spectra reveals that there is no particular single frequency within the band that might spoof the leak detector. The peaking at 35 kc is of interest in that it shows that each of these valve operations has an energy peak at the same frequency as a small gas leak in the laboratory. Table 3 lists an equivalent leak size and pressure that would generate a noise equivalent to that generated by valve operation. It turns out that these equivalent leaks are large and would require remedial action. From examinations of the spectrum it was concluded that valve operating noise is rather intense, and it would be expected that as far as normal hearing is concerned, it is about equivalent to the noise heard in a DC-6 aircraft. The ultrasonic noise level during nonoperation of the valves is about 101 db.

4. SPECIFICATION COMPLIANCE AND DEVIATIONS

As required by Task B, section 5 of Exhibit 1 of the contract, the ultrasonic leak detectors' resistance to rigid environmental conditions was determined. Since Task B, section 5, specifies that this determination shall not be of a destructive nature, primary determination was obtained by means of the following:

a. Physical examination of the equipment.

b. Analysis of drawings.

c. Literature search.

The results obtained are presented in this section along with recommendations for modifications to the detectors, which would make them suitable for use in the launch complex.

Also, as required by Task B, section 5, ultrasonic leak detectors were checked for conformity with MSFC-STD-110A and also with NBS-H-30 and NBS-HB-81. However, a few sections of this standard refer to sections in other specifications; and these, in turn, refer to still other standards, etc. Melpar project members exercised engineering judgment in determining which sections of these specifications were applicable and how far to go in tracing the ever-increasing number of specifications derived from the primary one.

Because of the greater sensitivity of the Delcon leak detector over the Techsonics, as well as its signal level indicating meter and obviously higher quality construction, it was judged that the Delcon unit was much more likely to be considered for use at KSC. Therefore, a heavier portion of the evaluation effort expended in this task was devoted to it. However, comments on the Techsonics may be found in sections 4.3, 4.4, and 4.5.

4.1 Delcon Deviation from Required Specifications

It is believed that the list of deviations of the Delcon ultrasonic translator from the specifications listed in the following paragraphs will be useful both in evaluating the Delcon and in preparing general specifications for ultrasonic translators.

4.1.1 Specification MSFC-STD-110A

4.1.1.1 Identification (4.3*): The Delcon does not have a suitable identification plate constructed and attached in accordance with Standards MC347, MC349, and MIL-STD-130. If this model of the Delcon ultrasonic translator is to be procured in its present form, it is suggested that the required plate be installed on the vertical centerline of the front cabinet, between the gain control and the output level meter. Another possible position for the plate would be at the top of the case under the carrying handle, where the present company plate is placed.

4.1.1.2 Component Identification (4.3.3*): Similarly, each component inside the Delcon assembly, including all resistors, transistors, and capacitors, must be identified with a legible marking as specified in MSFC-STD-141. The note mentioned in 4.2.1 of MSFC-STD-141 should be permanently and legibly marked on the rear of the Delcon chassis.

4.1.1.3 Enclosures (5.1*): The Delcon is not splashproof, as defined in MIL-STD-108D, section 3.21. Water drops striking the enclosure at angles considerably less than 100° from the downward vertical, as specified in the standard, may damage the speaker, which is not waterproof, by entering through the perforated metal plate in front of it. Although the jacks

* The numbers in parentheses refer to sections of the MSFC-STD-110A.

marked PHONES and RECORDER on the front assembly are well gasketed, the gain control and meter appear to be susceptible to water spray. The manufacturer's literature does, however, state that the Delcon has been designed to operate satisfactorily after being closed and exposed to rainfall at the rate of 4 inches per hour for 30 minutes. Because the unit is supplied with a well-made cover, the latter requirement can be met.

4.1.1.4 Terminals (5.4.1.1*): The power switch is equipped with screw terminals, rather than the required solder terminals.

4.1.1.5 Toggle Switch (5.4.1.2*): The switch has no moisture-proof seal around the handles.

4.1.1.6 Nonindicating Fuses (5.4.5.3.2*): The fuse holder at the left side of the Delcon should be approved as equal to Littelfuse Number 342001.

4.1.1.7 Cross-Recessed Screws (5.5.7.2*): Cross-recessed head screws are used in mounting an insulated 3-way terminal marked PROBE on the front panel of the Delcon. These chould be replaced by ordinary screws.

4.1.1.8 Self-Locking Nuts (5.5.7.3*): Most of the screws inside the Delcon are not equipped with self-locking nuts.

4.1.1.9 General Purpose (5.5.7.8*): Most general-purpose screws on the outer sides of the inner housing on the Delcon are hexagonal, slotted, rather than pan head and slotted.

4.1.1.10 Printed Circuit Board Design and Packaging (5.6*): The equipment deviates from this part of the specifications in items b, e, and g; the deviations are:

b. Floated bushing mounting connectors have not been used.

e. Packing density of printed circuit boards has not been maximized.

g. Printed circuit boards used are not standard ones fabricated of plastic sheet, laminated, 2-ounce copper-clad-type GE-glass-fabric epoxy base in accordance with Specification MIL-P-13949; however, they appear to be of equivalent quality.

4.1.2 National Bureau of Standards Specification NBS-H-30 (National Electrical Safety Code)

In order to meet paragraph 307, Hazardous Locations (item A, subitem 2 of Where Explosives or Inflammables Exist), the Delcon should be "surrounded with an enclosure of nonabsorptive, noncombustible material capable of withstanding without injury and without transmitting flame to the outside any explosion that may occur within."

4.1.3 National Bureau of Standards Specification NBS-HB-81

This specification calls out "Safety Rules for Installation and Maintenance of Electric Supply and Communication Lines." These items were covered in sections 4.1.1 through 4.1.2.

4.1.4 Discussion of Deviations

The Delcon Ultrasonic Translator Detector Model 118 presently costs $850.00. If the deviations from the rules in MSFC-STD-110A, NBS-H-30, and NBS-HB-81 (mentioned in sections 4.1.1 through 4.1.3) were to be corrected in-house by NASA, or by the manufacturer, i.e., the Hewlett-Packard Company, Delcon Division, the price of each unit as well as the time until the units become operational would very likely be considerably increased. There is also the question of whether the manufacturer would, himself, be willing to correct these deviations. Some of the deviations, such as the lack of an explosion-proof case, are significant and would have to be provided;

others are much less significant, such as the hexagonal shape of some screw heads on the sides of the inside case.

MSFC-STD-110A, NBS-H-30, and NBS-HB-81 all have provision for the waiving of their rules by the appropriate administrative authority. If it is decided to use the Delcon, the waiving of certain rules in many cases would be advisable.

4.2 Environmental Tests Met by Delcon Translator Detector

According to literature supplied by Delcon, the Delcon Translator Detector has passed the following tests.

4.2.1 Temperature

a. Nonoperating: The equipment, minus batteries, shall not be damaged by exposure to temperature ranges from -40° to $+160^{\circ}$F.

b. Operating: The equipment shall perform as specified during exposure to a temperature range from -20° to $+105^{\circ}$ ambient $+35^{\circ}$F solar rise.

4.2.2 Rain

The equipment shall be designed to operate satisfactorily after being exposed, in the closed nonoperating condition, to rainfall at the rate of 4 inches per hour for 30 minutes.

4.2.3 Humidity

The equipment shall perform as specified after exposure to a relative humidity of 95 percent.

4.2.4 Altitude

a. Nonoperating: The equipment shall not be damaged by exposure to an atmospheric pressure of 3.4 inches of mercury (50,000 feet).

b. Operating: The equipment shall operate satisfactorily while exposed to barometric pressure of 20.6 inches of mercury (10,000 feet).

4.2.5 Vibration

The specified equipment shall operate in accordance with specified performance after being subjected to continuous vibration along each of the three mutually perpendicular axes within the frequency range and amplitude as follows:

Frequency Range	Double Amplitude
5 to 15 cps	0.06 inch
15 to 25 cps	0.04 inch
25 to 55 cps	0.02 inch

4.2.6 Fungus

The equipment shall perform as specified after being subjected for extended periods to fungi and fungus supporting conditions.

4.2.7 Sand and Dust

The equipment shall perform as specified after extended exposure to sand and dust.

4.2.8 Salt-Sea Atmosphere

The equipment shall perform as specified after extended exposure to salt-sea atmosphere.

4.2.9 Tilted Position

This equipment shall perform as specified while its plane of operation is as much as 11° from the horizontal plane in any direction.

4.2.10 Wind Resistance

The equipment, closed for shipment, shall withstand winds of 70 mph with moorings and winds of 40 mph without moorings.

4.2.11 Snow Loads

The equipment shall withstand loads of 40 pounds per square foot without damage such that function would be impaired.

4.2.12 Radio Interference

Interference control shall be in accordance with MIL-I-26600. The unit, while operating, shall not generate radio interference of sufficient level to impair operation of the AN/ASG-21 Fire Control System or other normally concurrent operations of the B-52H Weapon System.

4.2.13 Shock

The equipment, in its case with all accessories in place, shall not suffer damage or subsequently fail to provide specified performance when the case is subjected to 20 g shocks.

4.3 Techsonics Deviation from Required Specifications

In general, all of the deviations of the Delcon mentioned in section 4.1 from required specifications appearing in MSFC-STD-110A, NBS-H-30, and NBS-HB-31 are also present in the Techsonics Series 110 Son-Tector Universal ultrasonic leak detector.

The Techsonics Series 110 translator detector costs only $150, considerably less than the $850 Delcon Model 118. However, the Delcon is 10 db more sensitive, more complex, employs better workmanship, and uses better quality components. The Eldevco, on the other hand, uses all-Japanese transistor-radio components, which may account in part for its relatively low cost.

Although the shortcomings of the Techsonics relative to the Delcon raise questions about its ruggedness and frequency of repair, the Techsonics guarantee is fairly comprehensive. The company literature makes the following statement:

"GUARANTEE: SON-TECTOR units are unconditionally guaranteed to perform as described and to be free of electronic or mechanical defects. Operating warranty extends for first year."

Despite its inexpensive construction it is judged that the Techsonics would fare about as well as the Delcon in the environmental regime discussed earlier, with the exception of exposure to rainfall, for the Techsonics has no cover. However, the Techsonics fails to meet the requirements of MSFC-STD-110A in many more respects than the Delcon, particularly those requirements which have to do with components.

4.4 Specifications Met by the Techsonics Series 110 Son-Tector

According to literature supplied by Techsonics, the Series 110 ultrasonic leak detector meets the following specifications:

a. Frequency response: Responds to sonic pressures in the range of 38,000 to 42,000 cps.

b. Sensitivity: Typically, can detect 0.010-inch diameter air leak at 5 pounds pressure from distances in excess of 50 feet.

c. Circuitry: All solid state. Uses silicon transistors throughout for high reliability and long battery life.

d. Earphones: Ear muffs to shut out ambient noise.

e. Output: 100 milliwatt audio.

f. Construction: Leather case and belt mounting.

g. Power Supply: Two self-contained 8.4-volt mercury transistor radio batteries--replaceable with standard 9-volt batteries.

h. Weight: Approximately 15 ounces, not including headset and probe.

i. Size: 1-5/8 x 4-1/8 x 6-1/8 inches.

4.5 Suggested Modifications to Ultrasonic Leak Detectors

The ultrasonic detectors under discussion are hand-carried devices used to survey for gas leaks, using the operator as a discriminator. The two detectors being considered have maximum response in the regions of 25 to 40 kc, which is about the spectral peak of this energy. This ultrasonic spectral region is transposed by heterodyning into the audio spectrum so that it can be heard from either the speaker or a headset. Many things, including keys, coins, cloth, telephone bells, typewriters, watches, corona, and, of course, gas leaks, and most normal room noises (but not speech), produce audible sound when transposed by the detector. Of the noises heard, cloth rubbing is the only one that might possibly be mistaken for a gas leak. If the ultrasonic detectors are to be used in an automatic alarm for leak-warning, changes would have to be made in the detector circuit to enable it to distinguish gas leak noises from other noises.

Although sufficient information is not now available for the design of these circuits, it is believed that analysis of the ultrasonic spectra obtained from fuelings will yield sufficient parameters for the purpose. In any case, for stationary service, the batteries should be replaced by a 115-volt 60-cps power supply.

The two detector units are translators; they take information from about 38 kc and move it down in frequency to the audio band. The cost of the units is vastly different: the Delcon about $850 and the Techsonics about $150. The Delcon sensitivity, 10 db greater than the Techsonics, may not have practical significance in detecting leaks, but complexity, quality of components, and workmanship favor the Delcon's estimated time to failure.

4.5.1 Delcon Unit

Specific recommendations for modifications that would enhance the usefulness of the Delcon unit under rigid environmental conditions are presented in the following paragraphs.

Two floating anchor nuts (No. 8) hold the mounting bracket at the base of the unit to the outer case. Forced vibration on the other side of the package from these small screws could cause them to fail, or the internal package to vibrate about its mounting bracket. The design of this mounting bracket, which supports the massive batteries, would permit the batteries and the remainder of the package to vibrate independently of each other, which could lead to fatigue and failures. The use of four cabinet-to-chassis mounting screws at both the top and bottom of the package could correct this situation.

Although fairly light, the main printed circuit board is securely mounted with six No. 6 screws. A prolonged 5 g vibration at the estimated resonant frequency of about 380 cps could deflect the middle of the board enough to crack it, or cause the heavier components to break loose from their mounting leads. At an impressed vibration frequency of 380 cps, the nonresonant deflection of the board at the center is calculated to be 0.00132 inch. If the board should have a mechanical "Q" of five or more, prolonged deflection might be sufficient to produce rupture. Deflection is calculated as follows:

$$I = \frac{bt^3}{12} = \frac{(0.090)^3(5)}{12} = 291 \times 10^{-6}$$

$$\text{Deflection} = \frac{PL^3}{192\varepsilon I}$$

At a load of 0.25 lb and $\varepsilon = 2{,}500{,}000$

$$D = \frac{0.25\ (5g)\ (7)^3}{192 \times 2{,}500{,}000 \times 291 \times 10^{-6}} = 0.00132 \text{ in.}$$

where

I = moment of inertia of board

P = force

L = length of board

ε = modulus of elasticity (glass-epoxy board)

t = thickness in inches

D = deflection

An additional mount in the center of the board would decrease the deflection by at least a factor of 5 by cutting the L dimension in the formula in half. The heavier components on the board, near the No. 6 screws, should be wrapped around terminals instead of mounted by leads.

4.5.2 Techsonics Unit

In order to make the Techsonics unit more useful under rigid environmental conditions, modifications should be made as described in the following paragraphs.

Mounting supports for the printed circuit board should be closer together and the batteries mounted in a different position. The many large components hanging by their leads should be close to the ends of the board and should be fixed in position with their longest dimension closest to the board.

The speaker requires protection from shock and vibration, and the unit should be mounted in an airtight purgeable container. The latter recommendation, if followed, would require the use of a remote loudspeaker or earphones.

It is judged that standard environmental tests could not be run without damage to the units, for a conventional vibration test would pass through the resonant frequency of the units and might be damaging. The standard shock test of a drop from 30 inches might cause permanent damage to the case, if not to the electronic components. The humidity test can be run at low temperatures for a short time, but rust, corrosion, and mildew on the leather case would be a problem. Salt spray would have a lasting deleterious effect.

5. CALCULATION OF LEAK RATE AND DISPERSION OF GASEOUS HYDROGEN

The problem of the determination of the hazardous area around a leak in the liquid hydrogen transport system is indeed a difficult one. The problem is composed of two parts: (1) determination of the leak rate of gaseous hydrogen, and (2) estimation of the diffusion of gas away from the leak.

5.1 Leak Rate of Gaseous Hydrogen

The problem here is to calculate the amount of gaseous hydrogen that would leak into the air through a cylindrical leak path having a length of 1 inch, a uniform width of 0.001 inch, and an outside diameter of 1.5 inch. The gaseous hydrogen is at a temperature just above the boiling point of liquid hydrogen, has a pressure of 40 psi, and leaks into an NTP air atmosphere.

For the solution of this part of the problem the discipline of fluid dynamics is used. The equation best describing the case at hand is that for Newtonian flow in a very thin annular slit as given by Fredrickson and Bird.[2]

$$Q = \frac{\pi R^4 P}{6\mu} (1-K)^3 \qquad (1)$$

Where:

Q = volume rate of flow through annulus

R = radius of outer cylinder of annulus

μ = Newtonian viscosity

K = ratio of radius of inner cylinder to that of outer cylinder

$P = (P_o - P_L)/L + \gamma g_z$

P_o = static pressure at entrance to annulus

P_L = static pressure at exit to annulus

L = length of annular region

γ = mass density of fluid

g_z = the component of gravitational acceleration in the direction of flow

The first assumption which has been made is that the leak takes place isothermally at 23°K. The viscosity of the gas was estimated at 1.2×10^{-5} poise from data given by Loeb.[3] All of the other factors were calculated from the given data and well defined physical constants. The volume rate of flow of gaseous hydrogen through the leak under these conditions is 866 cm^3/sec (at 23°K). This corresponds to 11.2 liters/sec at NTP, or a leak rate of approximately 1 gr/sec.

5.2 Dispersion of Gaseous Hydrogen

The second part of the problem is to calculate the distance from the source at which the concentration of gaseous hydrogen is one-half the lower explosive limit (LEL) or 2% by volume for the following conditions:

a. Dead calm

b. 15-knot wind blowing at 90 degrees to the direction of the leak.

Both of these conditions are idealized and impossible to work with without making further assumptions. Accurate results cannot be expected without making experimental measurements. However, by applying well known diffusion models it is possible to get an approximate solution to the problem.

For our model we have taken the AFCRL diffusion prediction equation.[4]

$$\frac{C_p}{Q} = \frac{0.00211\ (\Delta\ T+10)^{4.33}}{X^{1.96}\ \sigma^{0.506}} \qquad (2)$$

where:

C_p = concentration of the vapor in grams/m^3 at a distance X down wind.

Q = source strength in grams/sec.

ΔT = atmospheric temperature gradient between 6-foot and 54-foot level.

σ = standard deviation of the wind direction at the 12-foot level.

This equation gives inaccurate results for wind standard deviations of less than 8 degrees, calm winds, and temperature gradients in excess of +3 degrees. Table 4 shows the distance from the leak at which 1/2 LEL would be attained for various values of ΔT and σ. A wind standard deviation of 1 degree would reflect the worst case, where the hydrogen would diffuse in only one direction, while a σ of 360 degrees would approximate a completely random process such as might exist under conditions of dead calm. Cold gaseous hydrogen would escape from the leak at a temperature of 495°F lower than ambient, but would warm up as it traveled away from the source. It is for this reason that we have included the rather high values for ΔT.

Obviously, some of the values given in table 4 are in gross error. The major difficulty is in knowing what temperature differential to use in equation 2. A further complication arises in that this equation was derived for gases and aerosols which have approximately the same density as air. The density of hydrogen equals that of NTP air only at the boiling point of liquid hydrogen. Therefore, as hydrogen warms up it will rise rapidly and 1/2 LEL will be attained at far shorter distances than shown in table 4. However, for purposes of estimating the distance at which 1/2 LEL is attained, it is felt that the values calculated for the 3° air temperature differential will suffice. Then, in the case of dead calm, 1/2 LEL is attained at 16 meters from the leak, while with a 15 knot wind at 90° to the direction of the leak, 1/2 LEL is attained at 75 meters from the leak.

Once again, it should be emphasized that these calculations are necessarily crude, and experimental verification of these values should be obtained.

TABLE 4

DISTANCE[1 2] FROM SOURCE AT WHICH ONE-HALF THE LOWER EXPLOSIVE LIMIT IS ATTAINED FOR VARIOUS TEMPERATURE GRADIENTS AND WIND STANDARD DEVIATIONS

$\frac{1}{\sigma}$ (Degrees)	Normal Condition -0.9°F	Inversion Condition 3°F	10°F	100°F	495°F
1	33.8	74.4	193	8330	241,000
8	19.8	43.5	113	4870	141,000
14	17.1	37.7	97.5	4210	122,000
360	7.4	16.3	42.2	1820	52,800

1. Distances are in meters.
2. Buoyancy of H_2 is neglected.

6. REFERENCES

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